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**ERRATUM.*

Line 5 under B. General Description on page 60 which reads, " rocks, stands, on the average, 800 or 900 ft. above the sea, and is, broadly," should read : " rocks, stands, on the average, 800 or 900 ft. above the sea. The rest of the strip averages not more than 300 to 500 ft. above the sea and is, broadly."

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SOIL CONSERVATION IN WESTERN AUSTRALIA WITH SPECIAL REFERENCE TO AVENUES FOR FURTHER SCIENTIFIC INVESTIGATION.

PRESIDENTIAL ADDRESS, 1951.

BY

G. H. BURVILL, M.Ag.Sc.

Delivered 10th July, 1951.

INTRODUCTION.

Soil Conservation is of great importance to Western Australia even though its vast area of almost a million square miles is only lightly populated at present by 580,000 people. Its importance to the State has been recognised in the Soil Conservation Act, 1945. "An Act relating to the Conservation of Soil Resources and to the mitigation of Erosion." The author in his official position of Commissioner of Soil Conservation under this Act directs a Soil Conservation Service, the objects of which are briefly : To prevent and cure soil erosion ; to promote soil conservation and to educate landholders and the public in the need for, and ways of, soil conservation. Four years experience in this position and a much longer period of studying the soils of Western Australia from various aspects have focussed attention on a number of gaps in our knowledge which have a direct bearing on soil conservation and soil erosion control. These are brought forward in this paper in the hope that they may offer avenues for further scientific investigation within the State.

The soils of the earth are basic to mankind's existence, for, through native plants or cultivated crops and pastures which the soil supports, the human population derives much of its requirements of food, clothing, warmth and shelter. Soil is not essential for plant growth but there is no other practical medium which could be brought into use in sufficient extent to replace it. Failure to handle and treat soil properly resulted centuries ago in the desolation of parts of the earth especially around the Mediterranean Sea. The "dust-bowl" conditions in U.S.A. 15 to 20 years ago are a more recent reminder of this menace, and so in recent years a great upsurge of interest and action in soil conservation and soil erosion control has followed the efforts and example of the United States of America.

The world's population is increasing and we are well aware of the recurring food shortages of overpopulated parts of Asia. Some who have studied these questions believe that the world's soils will be unable to support its future population. Others believe that, provided soil resources are conserved and scientific knowledge and technological advances are applied to agriculture, it will be possible to feed a much larger world population. Without attempting to say which view is correct, one can be sure that there is abundant need for great care in the use of the soil.

DEFINITIONS—SOIL AND SOIL CONSERVATION.

It is desirable to define the terms *soil* and *soil conservation* before proceeding to discuss either under Western Australian conditions.

Soil is the upper few feet of the more or less unconsolidated layer which overlies the hard rocks of the earth's crust. It is the natural medium in which most plants grow, or more strictly, from which they receive support, and obtain most of their essential requirements of water and a number of elements. Soil consists of mineral matter from rocks, altered to some extent and enriched by remains of plants and animals which have lived on and in the soil. These organic remains, an essential part, are often called humus. They are found in a surface layer usually less than a foot thick and are of great importance in determining soil fertility. Moisture and the gases of the soil atmosphere are also essential parts. Soil varies from place to place depending on rooks, climate and biotic factors. It is obvious that in the study of the soil is a meeting place for the interests of several sciences including geology, mineralogy, botany, zoology, microbiology, meteorology, physics and chemistry.

Soil has been referred to as "the outward expression of the reactions between animate and inanimate nature." It is not static. The processes of natural erosion are constantly removing parts of the soil but it is renewed by rock weathering and by living processes.

Soil conservation is related to man's usage of the soil to meet his needs of food and fibres, timber and fuel. Soil conservation means using the soil in such a way that it remains substantially in place and is treated so that it will be able to produce for future generations as well or better than it can at present. The whole gamut of agricultural, pastoral and forestry practices thus comes under review in considering ways and means of soil conservation. Man induced soil erosion is the most obvious indication that land use is not properly adjusted to the climate and landscape.

LAND USE AND LAND USE POTENTIAL IN WESTERN AUSTRALIA.

Climate and soil largely determine the use of land by man. Only where irrigation is possible can the dominating influence of climate be set aside. Thus we find that, due to low and uncertain rainfall, vast areas of Western Australia are used only for extensive grazing by sheep and cattle, or are not used at all by white men. About one-ninth of the State in the south-western part has a climate suitable for agriculture and about one-quarter of this area, *i.e.*, about 17 million acres, has been cleared of its natural vegetation and devoted to crops and pastures (see text fig. 1). Great expansion seems possible in these favourable climatic areas in spite of certain soil deficiencies discussed later. The Mediterranean type of climate with annual rainfalls of 11 to 60 inches, mostly falling in the mild winter period, enables a system of agriculture and grazing to be followed based on annual crops and pastures adapted to winter and spring growth. Wheat, oats, barley and subterranean clover (*Trifolium subterraneum*) are the mainstays, supported by superphosphate fertiliser to overcome the general deficiency of soil phosphate.

The vast central area of the State extending from the north-west to the east and south-east, with a rather unreliable rainfall averaging less than 11 inches annually, is unlikely to be devoted to agriculture except in small areas under irrigation. Its pastoral industry, based on the natural shrubs and herbage, supports about 2,500,000 sheep and 60,000 cattle. Prior to 1936 numbers were at least 50 per cent. greater. Recurring droughts, as well as wild

dogs and kangaroos, limit the stock numbers, and deterioration of herbage along with some soil erosion has occurred. Soil conservation and productive capacity under such conditions will require constant attention to rates of stocking and vermin control, but research may point the way to regeneration and improvements. Collaborative work on north-west pastoral problems by the State Department of Agriculture and the University Institute of Agriculture has already been initiated.

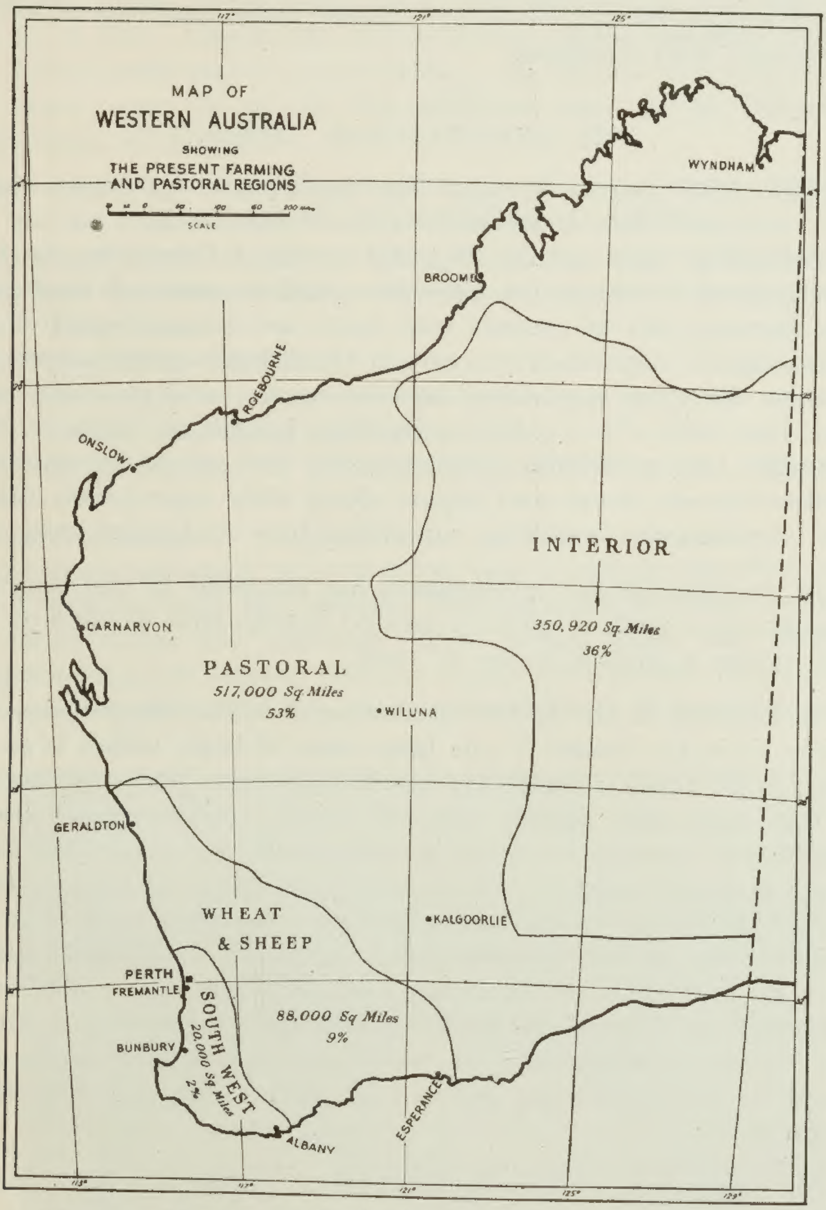

Fig. 1. This map reproduced from the 1943-44 Annual Report of the Surveyor General shows that agriculture is confined to about 11 per cent. of Western Australia in the areas marked "Wheat and Sheep" and "South-West." The area marked "Interior" is not occupied by white men.

The summer rainfall tropical regions of the State extending from around Port Hedland and Marble Bar, through the Kimberleys to Wyndham receive from 11 to 60 inches annual rainfall. The rain is less reliable than in the south-west, and high temperatures reduce its efficiency for crop growth. The length of the growing season is less than five months except in the extreme north (Prescott and Thomas, 1948–49). Agriculture under natural rainfall seems unlikely except in limited areas but irrigation could open up possibilities on alluvial plains which separate the massive and rugged hills and ranges. This aspect is under investigation at the Kimberley Research Station on the Ord River about 50 miles east of Wyndham.

The natural grasses and shrubs of this large tropical area are now grazed by 450,000 cattle and 600,000 sheep. The more or less unrestricted grazing of stock has resulted in severe water and wind erosion in some parts especially in the Ord River basin of the East Kimberley and no practical solution is apparent. Better control of the grazing animals is an obvious need. Ecological studies in these areas may lead to improvements and new introductions of grazing plants are a definite possibility in some parts as shown by the spread of the introduced buffel and Birdwood grasses (*Cenchrus ciliaris* and *Cenchrus setigerus*) around Port Hedland.

THE AGRICULTURAL AREAS.

As already stated, agriculture, as distinct from the extensive pastoral use of land, is confined almost entirely to the south-western part of Western Australia extending from Ajana, 50 miles north of Geraldton, to Esperance on the south coast. Sixteen or seventeen million acres of land have been cleared for farming and at present new areas are being cleared of the more or less useless native vegetation at a rate of about half a million acres annually. There is scope for great expansion because science and practical experience have shown that soils of low inherent fertility, judged on chemical standards, can be brought into profitable production by the use of leguminous plants such as subterranean clover and lupins along with appropriate mineral fertilisers and supplements including superphosphate and some trace elements.

Most of the agricultural development has occurred in the past 40 years. Only a quarter of a million acres of cleared arable land existed in 1890 and it was still under a million acres in 1905.

Soil conservation in the agricultural areas is of vital importance now, and will continue so in the future if this large area of land, which is so favoured climatically, is to make its rightful contribution in food and fibres to the needs of the Australian nation and the world. Soil erosion, induced by man's activities in farming the land, is widespread, even now, but fortunately is not severe in most localities. Both erosion by wind and by running water occur, the former mainly in the drier wheat growing areas with 11 to 15 inches annual rainfall and the latter principally in the 15 to 30 inch rainfall belt. In the high rainfall areas of the south-west with annual rainfall from 30 to 60 inches most of the cleared and part-cleared land is devoted to sown pastures. Soil erosion is not common, but on very steep slopes in orchards and cultivated paddocks soil erosion by water, and damage by small landslides, are not uncommon.

The Soil Conservation Service established under the Soil Conservation Act 1945, is devoting its efforts to the prevention and cure of soil erosion, but continually emphasizes the need for a conscious effort towards soil conservation in all farming practices. Technical advice and assistance are being provided through a staff of agricultural scientists and technicians. About 40 demonstration experiments mostly involving the construction of contour banks, contour pasture furrows, gully filling and contour working have been carried out in various districts in co-operation with farmers, to try out various soil erosion control measures under the soil and climatic conditions of the various localities. A large number of farmers have been advised on, and assisted with, various soil erosion control problems.

The prevention and cure of soil erosion on farmlands largely involves adjusting farming practices so that the soil will not be unduly exposed to the erosive forces of wind and rain. The agricultural areas of Western Australia

receive about three-quarters of their rain in the winter period May to October. There are erosion hazards from rainfalls of moderate intensity falling in May and June when cereal crops are just planted and the soil surface is loose and nearly bare. Summer thunderstorms in the January to April period are irregular but have often caused erosion damage on bare fallows, orchards, and sloping paddocks where grazing had removed nearly all the plant cover. Strong winds from various directions have caused soil drift, especially in summer, on sandy surfaced areas which have been bare fallowed or left almost bare by overgrazing or fire. Cereal rye has proved a most valuable crop to plant on wind eroded areas and to check drifts. Its use for this purpose is extending. In many cases the rye on the stabilised area can be followed by subterranean clover or lupins.

SOME UNUSUAL FEATURES OF THE SOILS OF THE WESTERN AUSTRALIAN AGRICULTURAL AREAS.

Three features of the soils of the agricultural areas of Western Australia deserve special discussion because all have an important bearing on soil conservation. They are :—

(a) Phosphorus deficiency.

(b) The extensive occurrence of sandy and gravelly soils associated with laterite or ironstone.

(c) The occurrence of water soluble salts especially sodium chloride.

Phosphorus Deficiency.

Phosphorus deficiency is so general that a soil is regarded as rich and fertile if it requires only the addition of phosphatic fertiliser to make it productive under crops and pastures. Most areas, when first cleared of the native vegetation grow little or nothing if planted to cereals or pastures without phosphate. (*See* text fig. 2.) Regular additions of superphosphate have

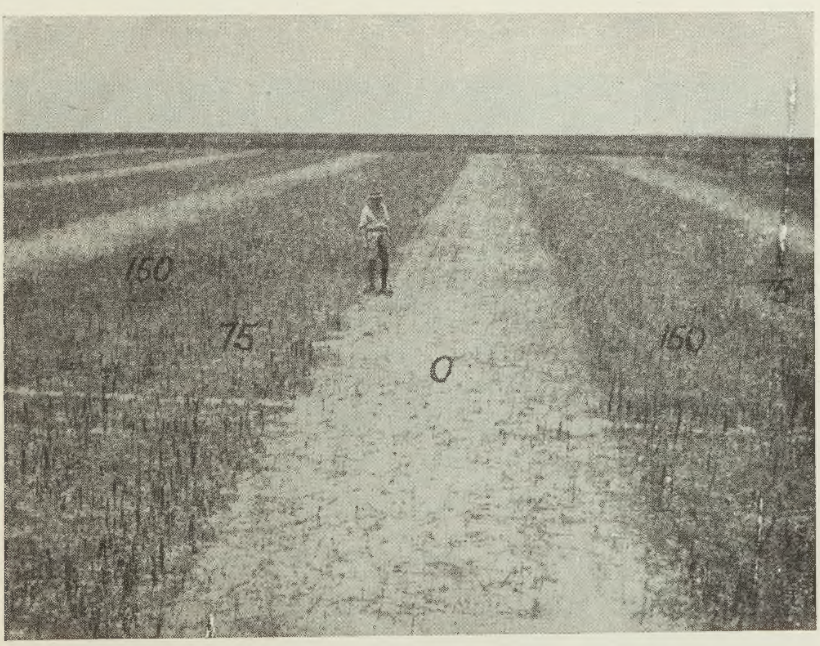

Fig. 2. Phosphorus deficiency in Western Australian soils is illustrated by a rate of superphosphate experiment at Wongan Hills Agricultural Research Station Plots which have never received superphosphate grow practically nothing even after 20 years' farming, while adjacent plots which have received five dressings of "super" at 75 or 150 pounds per acre carry good volunteer pasture.

built up a phosphate reserve in areas farmed for 10 to 50 years. To maintain the productivity of developed areas and to undertake the vast potential expansion which may be envisaged will require an expanding supply of phos-

phatic fertiliser. But it also requires the devlopment of suitable chemical methods or plant growth techniques to assess the need of soils for phosphatic fertiliser. Experience and experiments in the past ten years have shown that after several applications of superphosphate amounting to perhaps half a ton in all, the residual effect becomes substantial on many soils. Smaller annual additions of superphosphate then suffice to produce good returns (Teakle and Cariss, 1943).

The Gravelly and Sandy Soils Associated with Laterite.

Most of the agricultural areas of Western Australia are underlain by very ancient rocks of Precambrian age with granite and gneiss predominating. Rocks of Permian and younger age occur in a coastal strip and have their greatest extent in the country between Perth and Geraldton where they go inland about 60 miles (Jutson, 1950). Miocene sediments occur in the southern areas between Albany and Esperance but are not completely mapped. But in spite of geological uniformity over large areas, a complex soil pattern occurs in many parts. Soils are found with characteristics related to the present climatic conditions, especially the decreasing rainfall going inland from the south-west corner. But throughout the whole of the agricultural areas and beyond, irrespective of rainfall, are vast areas of acid soils containing ironstone gravel and of low inherent fertility. (*See* text fig. 3.) They are generally in the higher parts and are frequently associated with hills capped with massive ironstone or laterite. Laterite and the associated soils have been studied by geologists, mineralogists, and soil scientists and are now generally believed to be the result of weathering and soil forming processes on a relatively flat topography with alternate periods of waterlogging and drying. The vast areas of laterite and associated soils in Western Australia are relics of an earlier wetter climatic cycle when the drier inland areas, at least, were much wetter than now. Prescott (1944) calls these soils residual podsols.

Fig. 3. Scrubplain soil profile showing sandy surface and dense ferruginous gravel in subsoil. Such soils and related types occur over vast areas and are being extensively developed for crops and pastures.

The sandy and gravelly soils associated with laterite are estimated to cover at least half and possibly more of the area in which the climate is suitable for agricultural development. Extensive farming of these soils has already occurred both in high rainfall districts and in the wheatbelt. In the latter case these light lands have usually been developed in conjunction with better soils. But experience has shown that even after the acute phosphate deficiency is overcome these laterite soils or " residual podsols " have comparatively low agricultural productivity unless a leguminous plant such as subterranean clover or lupin is introduced. Subterranean clover and superphosphate have been the basis of extensive development of pastures for dairying in districts with over 30 inches annual rainfall. In 15 to 30 inch rainfall areas the same combination is extensively used in sheep pastures and much better cereal crops can now be grown in rotation with the clover than before its introduction. The early maturing strains of subterranean clover are being extensively planted on the light lands with annual rainfalls as low as 14 inches. Many millions of acres of similar light lands occur where the rainfall is less than 14 inches. Soil conservation and a stable agricultural system for such lands under these low rainfalls will depend on finding or developing a suitable legume which will persist under proper management. Fortunately research in various aspects of this problem is actively in progress at the University Institute of Agriculture and in the State Department of Agriculture.

In some areas the sandy and gravelly soils associated with laterite have been found to require additions of copper, manganese or zinc for the satisfactory growth of oats, wheat, barley or subterranean clover. As already indicated the majority of the undeveloped soils in the agricultural areas are these sandy and gravelly types, so that a continuance of active research in plant nutrition is an obvious need for future soil conservation.

Soil Salinity.

The occurrence of unusual amounts of water soluble salts, principally sodium chloride, in the soils of the agricultural areas has given rise to a problem of great complexity in soil conservation and soil erosion control (Burvill 1947). If the concentration of water soluble salts in the soil moisture becomes too great, most plants, including the common agricultural crops, are unable to take up their moisture requirements and growth is restricted or entirely prevented. This a common agricultural problem but is principally associated with irrigation in dry climates. In Western Australia, bare sterile patches due to surface concentration of salt are common on farmlands. They have developed under natural rainfall conditions and the sytem of agriculture based mainly on annual crops and pastures. The affected areas are mostly in the districts devoted to cereals and sheep with 11 to 30 inches annual rainfall. On many farms the salt areas are very small but are foci for soil erosion especially on slopes. In other cases large areas are salty and further areas are threatened as discussed later.

The primary source of the salt is believed to be oceanic spray carried inland and brought to earth as dust or by the rainfall. Some may represent residues from a submersion of the southern part of the State beneath the ocean in Miocene times. The rainfall per wet day averages less than 20 points in most of the areas where the salt problem occurs. Under virgin conditions most of the rain was apparently absorbed near to where it fell and was utilised by the native vegetation or found its way into the deeper layers of soil and weathered rock. A large part of the salt accumulated

in soils and subsoils. The evergreen native vegetation has been removed during the past 50 years from some 12 to 14 million acres of land and a system of agriculture using mainly annual plants has been substituted. Changes in soil moisture conditions have occurred and in numerous places movement of moisture to the soil surface has caused salt concentration.

Three types of salt affected land may be recognised :—

(1) In the 15 to 30 inch rainfall areas springs and seepages develop after clearing on slopes and adjacent to gullies and drainage lines. They often provide useful soaks of stock water but, as evaporation proceeds, salt concentration occurs and produces bare sterile areas. These bare areas are often eroded by running water and the rills and gullies eat back into further good land.

(2) In the 12 to 15 inch rainfall areas of the outer wheat belt many extensive flats are becoming salted because the ground water level has risen to within five to six feet of the soil surface. (*See* text fig. 4.) From this shallow depth, moisture reaches the surface in dry weather and concentrates salt. Before the land was cleared salt water is reported to have occurred at 15 to 30 feet. This water table rise is an increasing problem and the affected areas are usually the better types of land. Some of the water table rise is apparently through surface flooding by runoff from higher ground after heavy rains, but some moisture is also believed to reach the flats by subsoil seepage from higher ground.

Fig. 4. Native vegetation of Eucalypts and scrub killed by changes in ground water level and consequent soil salinity. The salt tolerant samphire (Salicornia sp.) is now colonising this flat.

(3) Some of the heavier soils of the outer wheatbelt with 11 to 13 inch rainfall contain large amounts of salt in the upper three feet of the soil. After clearing redistribution of salt causes systems of bare sterile patches to develop, even at high levels in the countryside. Any of these bare patches may become a focus for wind or water erosion.

The foregoing description of the causes and manifestation of the salt problem is partly theoretical. Further information about ground water movements is especially necessary and the relation of these movements to the change over from evergreen native vegetation to the annual crops and pastures and bare fallows of the present agricultural system. The problem of valley waterlogging described under (2) above is a paradox in an area where so much attention has been given to "dry" farming ; *i.e.*, a system of farming involving bare fallows and early maturing quick growing cereals bred and selected to grow and mature during the winter and the comparatively dry spring months. It seems that the evergreen native vegetation exercised a control over soil moisture which has been lost or greatly modified since large areas have been cleared for farming. What further changes may be expected if the area of cleared land is doubled during the next 25 to 50 years ? Are the flatter lands of the broad valleys which characterise the topography of the 11 to 15 inch rainfall belt doomed to further waterlogging and salting ? There is scope for much fundamental and practical investigation in this broad soil conservation problem.

One of the basic principles of soil conservation and soil erosion control is to encourage the absorption of rainfall as soon as possible after it reaches the ground so that the risks of erosion by running water are reduced to a minimum and so that flood hazards to lower lands may be avoided. The maintenance of a protective cover of living or dead vegetation is a further important principle. The evergreen native vegetation of the agricultural areas achieved these objectives but our agricultural crops and practices have been less successful. The dry farming areas have, after 30 to 40 years of development, a surplus of ground water charged with salt in many places. Can any way be found to drain away or utilise or control this surplus ? Fortunately all the consequences are not on the debit side. Supplies of potable water for stock and man have been more readily obtained several years after the natural vegetation has been removed, especially in areas of light land or sand plain.

The moisture requirements and the water absorbing habits of the native vegetation would be a valuable study in elucidating some aspects of the salt problem. From the consequences of removing this vegetation, it would appear that the sown and volunteer annual plants on our farmlands utilise less of the rainfall than did the evergreen native plants. The latter have been evolved and adapted to survive as evergreens in a climate with a long hot dry summer, so perhaps they absorb water very vigorously in winter or after any wet periods. Can we find or develop pasture and crop plants which will absorb more water in winter when most rain falls, especially in June, July and August when temperatures and length of day tend to restrict growth ? Can we eliminate bare fallow so that living plants will be left to utilise winter moisture ? This aim may appear to be in direct contradiction to one of the main stated aims of fallowing, *i.e.*, moisture conservation for a succeeding crop. But doubts increase whether the benefits of fallowing (where there are benefits) are due at all directly to moisture conservation.

The problems of soil salinity, springs, soaks, valley waterlogging and associated soil erosion by water and wind are all basically related to soil moisture movements which require to be studied more from every possible angle by climatologists, agriculturists, botanists, geologists, soil scientists, and engineers.

Enough has been said to present the view that agricultural development in Western Australia has taken place and is continuing in a rather unique natural combination of soils and climate. The past geological conditions and the past as well as the present climatic conditions have exerted a strong influence in determining the characters of this combination. The native flora is well known on account of its unusual genera and species, but its unusual characters with respect to soil moisture usage and control, are, so far, only known by inference from the changes which have followed the removal of the native vegetation to make way for man's agricultural pursuits.

CONCLUSIONS.

Soil conservation in Western Australia, especially in the agricultural areas, can be viewed against a background which shows the results achieved and the problems developed mainly during the past fifty years. If the obligation is accepted now to consider soil conservation for centuries ahead then all aspects of the environment related to soils and land use deserve continuing study by scientists in various related fields.

The following avenues are suggested as worthy of further studies :—

1. *Climate* (both present and past).—In the present climate more precise data are required for various agricultural centres on the frequency and intensity of rain storms which can cause soil erosion. Past climate and climatic changes are apparently responsible for the laterite and the scrub plain soils and also possibly for many features of the inland salt lake sytems and their associated soils.
2. *Geology of the Agricultural areas.*—The underlying rocks give the parent material for the soils. But besides knowledge of the hard rocks more information is needed about the weathered rock ; its nature and composition ; how it holds or transmits water soluble salts ; its movements and relation to physiography ; in fact all aspects of what may be called surface geology.
3. *Hydrology of the agricultural areas.*—The study of all aspects of the movement of water through and over the land after it falls as rain is important wherever soil conservation and erosion control are being considered. As already indicated this assumes special importance because of the problems of soil salinity and valley waterlogging.
4. *Physiological Studies of the Native Vegetation.*—Precise studies with respect to water requirements and salt tolerance of the native flora might lead to a clearer understanding of the agricultural problems of soil salinity and valley waterlogging.
5. *Agricultural Engineering.* Machinery and methods for soil cultivation, earth-moving, and drainage, to promote soil conservation, need to be considered along with hydrology and cropping practices.
6. *Soil Science.*—Studies in this field will be closely related to surface geology discussed under (2) above. The special effects of soluble salts on the nature of the soils and subsoils and the occurrence and movement of soluble salts in soils are worthy of special attention as the fundamental information about the soil pattern is being extended.

7. *Agricultural Science.*—All agricultural research is directed towards improving the general efficiency of agricultural production. Obviously soil conservation must receive due attention in such research. The objectives of maintaining protective cover on the soil surface and of maintaining or improving soil fertility suggest the special need in Western Australia for work on :—

(a) Soil deficiencies, especially phosphate and trace elements, but not excluding other essential elements.

(b) Crop rotations, particularly with the objective of reducing the areas under bare fallow.

(c) Selection and development of pasture and crop plants for controlling or utilising excess winter moisture as well as for their part in soil fertility maintainance.

(d) Studies of salt tolerance of crops, pastures, shrubs and trees.

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1.—THE SAHUL SHELF, NORTHERN AUSTRALIA; ITS STRUCTURE AND GEOLOGICAL RELATIONSHIPS.

By

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CONTENTS.

ABSTRACT.

The Sahul Shelf (*sensu stricto*) is defined as lying north of Australia between the Arafura Shelf and the Rowley Shelf. In its broader sense it includes these adjacent shelves, which are drawn closely into this study. A series of transverse "rises" (Dampier, Leveque, Londonderry, Van Diemen, Wessel, Aroe), across the shelf, separates a series of "depressions" (Rowley, Browse, Bonaparte, Arafura, Carpentaria). The rises average 10–40 and the depressions 40–70 fathoms in depth. Coral reefs occur on the rises, and near the outer edges of the depressions are perfect atolls, where the shelf edge is as low as 300 fathoms. Sedimentation is mainly calcareous debris near the reefs, while elsewhere are glauconitic and residual quartz sands and muds.

The rises on the shelf occur opposite positive Pre-Cambrian blocks on the mainland and the depressions opposite negative (paralic) basins lying between. The latter may contain 25,000 feet of Palaeozoic, Mesozoic and Tertiary shallow-water sediments. The positive blocks show only a thin veneer of sediments on the Pre-Cambrian basement. The Aroe Islands have a core of granite overlain by a thin cover of Tertiary and Quaternary, like southern New Guinea with its Mabaduan granite. No true orogenic folding occurred since middle Pre-Cambrian. Epeirogenic movements were early Caledonian, post-Permian and late Tertiary. Margins of blocks are marked by taphrogenic features: faults and flexures and "Saxonian" type folds.

Contemporary seismic disturbances along shelf margin are correlated with the buckling of the outer East Indian mobile belt. The surface of the shelf was terraced during low eustatic Pleistocene sea-levels, when small "canyons" were formed. Tectonic subsidence as well is needed to explain the closed basin on the Bonaparte Depression and the atoll-crowned marginal depressions.

I. INTRODUCTION.

The Sahul Shelf is taken here as that part of the Northern Australian continental shelf which corresponds approximately to the area occupied by the Timor Sea. Farther east the northern Australian shelf extends right across to Aroe and New Guinea, the Arafura Sea area ("Arafura Shelf"), even to the Gulf of Carpentaria. To the west it reaches to North-West Cape ("Rowley Shelf"). The writer is following Schott (1935) in regarding the whole area as part of the Indian Ocean.*

* There is a disagreement as to the boundaries of the Indian Ocean in this region. Kossinna (1921) restricted it to west of a line running through Cape Talbot (the northern tip of the Kimberley, 50 miles E. of Cape Bougainville) to the Sahul Bank and Timor. The International Hydrographic Bureau (Anon. 1928) placed all east of Cape Bougainville in the East Indian Archipelago, which belongs to the Pacific Ocean. Such divisions appear to be indefensible from both oceanographic and geographic points of view, for these arbitrary lines cross the middle of the Timor Sea and cut structural boundaries as well. Schott selected the only *natural* boundary between the Indian and Pacific Oceans, viz., Torres Straits.

Northern Australia, with its off-lying shelf and islands is one of the least known regions of the world. The available material is meagre and there are large blanks on the geological maps. There are no satisfactory topographic maps as yet, and even the nautical charts bear the following significant warning: "Caution—the whole of the coasts of North-western Australia are as yet very imperfectly examined and charted, and mariners are cautioned accordingly."

Abel Tasman was the first to prepare a rough map of this coast in 1644. William Dampier (1703) was singularly unimpressed by it, and it was only in the early nineteenth century that formal charting was begun. British naval surveyors then covered the area rather generally (King, 1827 ; Stokes, 1846 ; see historical review : Fairbridge, 1948).

A collection of rocks from these shores was described by Fitton (King, 1827 appendix), and late in the last century Hardman investigated reputed gold discoveries in the hinterland of the Kimberley and H. Y. L. Brown in the Northern Territory. The Geological Survey of Western Australia, the State geologists of South Australia's Northern Territory dependency and later various federal ventures, including the Northern Australian Geological and Geophysical Survey in the thirties of the present century, have all made useful contributions but there has been no comprehensive survey of the region.

Recent works on the stratigraphy of Western Australia are by Teichert (1947), on the Northern Territory by Voisey (1939), on the Pre-Cambrian by Clarke (1938), on the tectonic patterns by Hills (1946), on the coral reefs by Teichert and Fairbridge (1948), and Fairbridge (1950). Indispensable references are the British Admiralty "Pilot" and charts, especially numbers 1039, 1047, 1048, 2759A, and Australian Hydrographic Branch charts, numbers AUS.087, 088, 089, 094 and 097.

The present writer was attracted by the problems of this area during war-service with the R.A.A.F. Experience of the Kimberley was also obtained while engaged in an oil survey for the Caltex Co. in 1941. Aerial photos, new naval charts and other data now shed light on the general geology and structure of the region.

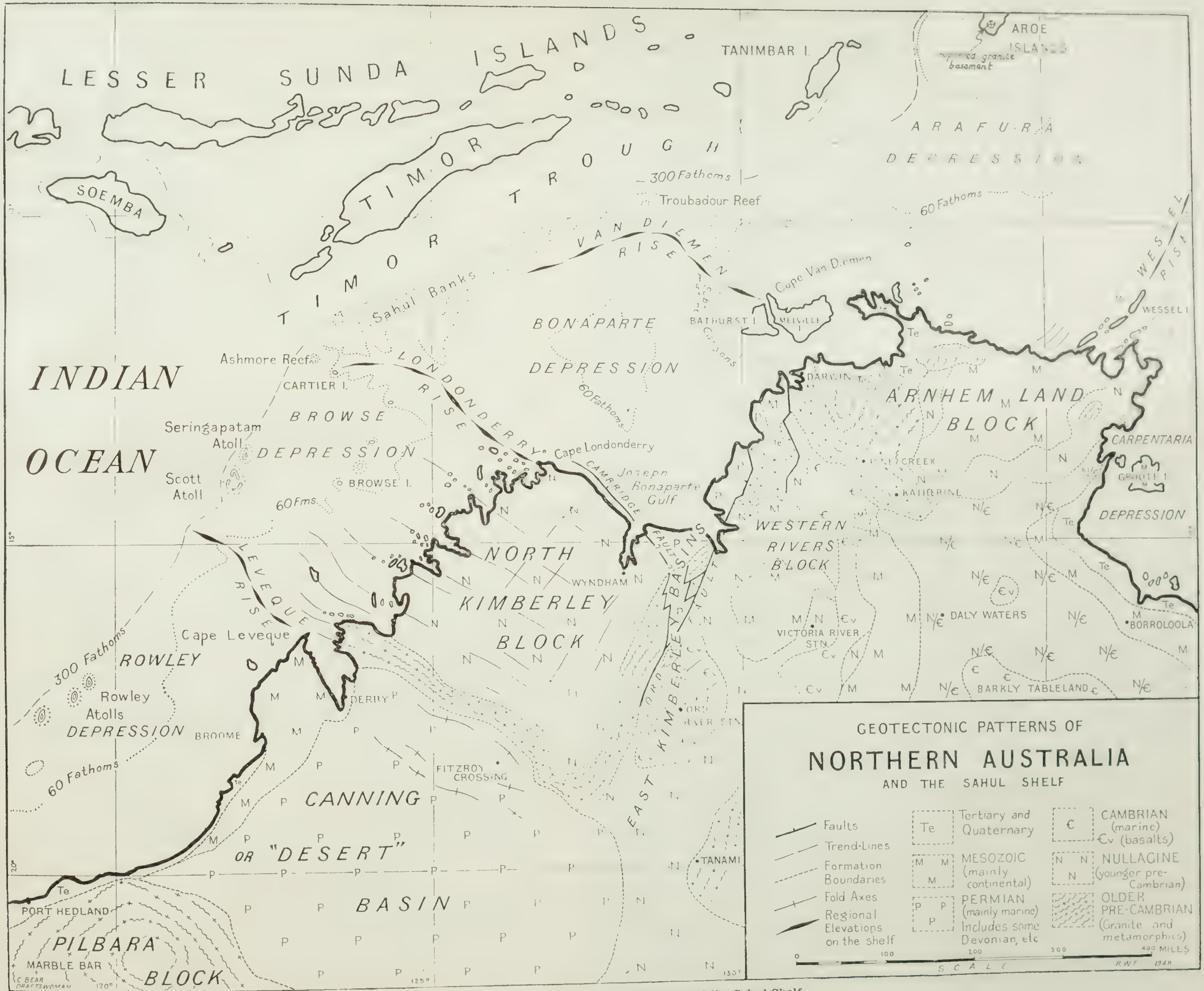
Acknowledgement is hereby made to the Commonwealth Universities Research Grant for financial assistance covering the typing, and to Dr. Curt Teichert for stimulating discussions. Valuable help with the drafting has been provided by the Chief Draftsman, Lands Department, Perth.

II. BATHYMETRIC MATERIAL.

(a) *Dimensions and Definitions.*

The Sahul Shelf is sometimes taken to cover the entire northern border of Australia, extending 2,000 miles from North-West Cape and Exmouth Gulf in the west to Dutch New Guinea and Torres Straits in the east, but here it is restricted to the central part, an area 500 miles long and 200 miles across. Its seaward limit is generally given as the 100 fathom contour, but should be placed at the 300 fathom line. Its northern edge comes within 75 miles of Timor, from which it is separated by a long "deep" of over 1,000 fathoms, known as the Timor Trough.

The existence of the northern Australian Shelf was first recognised as a major earth feature in 1845 by Earl, who identified both a "Great Asiatic Bank" off Malaya (the Sunda Shelf) and a "Great Australian Bank" off

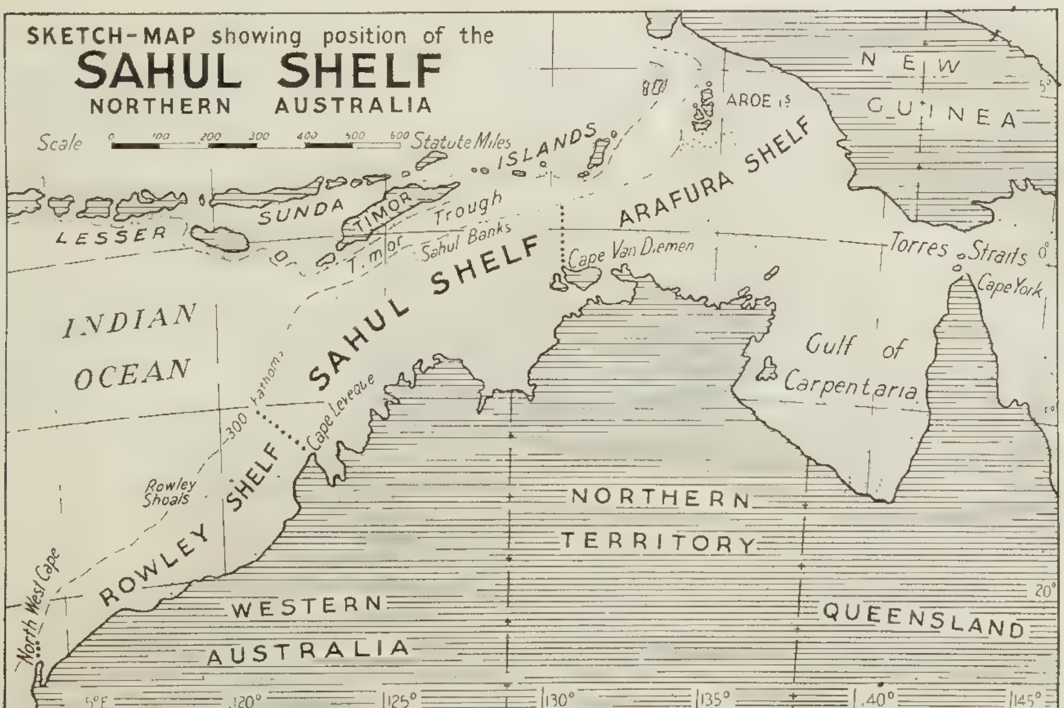


Geotectonic Patterns of Northern Australia and the Sahul Shelf.

northern Australia. Krümmel (1897, vol. 1, p. 113) divided it into two, an "Arafura Shelf" of 930,000 sq. km.* (between Cape van Diemen and New Guinea), and a "North-West Australian Shelf" (covering 590,000 sq. km., between North-West Cape and Melville Island).

Without reference to Krümmel, Molengraaff introduced the terms "Sunda Shelf" and "Sahul Shelf" for the two great platforms previously recognised by Earl (Molengraaff and Weber, 1919; Molengraaff, 1921). "Sahul" comes from the small Sahul (Sahoel) Banks which lie on the shelf south-east of Timor and were so named four hundred years ago on Dutch charts of the area (Fairbridge, 1948).

Amongst geologists a loose application of this term "Sahul Shelf" has become rather general (Brouwer, 1920; Zwierzicki, 1927; Kuenen, 1935), but it is convenient to restrict it. Krümmel has previously named the eastern part the "Arafura Shelf," and it seems desirable to subdivide the western part into two, the natural division being an important tectonic line running north-west from Cape Leveque (from 16°20′S., 123°E. to 15°S. 121°E.), each being nearly 300,000 sq. km. The central area would be the "Sahul Shelf" (*sensu stricto*), and for the western area the term "Rowley Shelf" is proposed.



by- R.W FAIRBRIDGE · University of W.A

Text Fig. 1.—Sketch-map showing position of the Sahul Shelf, Northern Australia.

(b) *Edge of Continental Shelf.*

The steep continental slope in this region begins at about the 300 fathom contour, as noticed already by Kuenen (in Vening-Meinesz, 1934, p. 191). He first took it to be at 1,000 metres, but later corrected it to 500 m. (1935, p. 18).

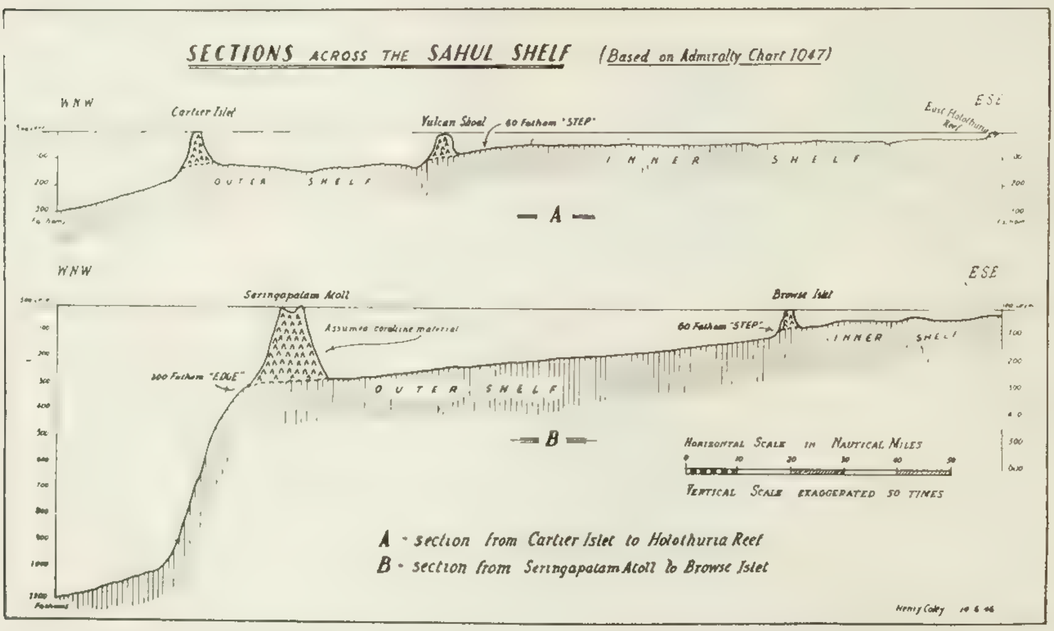
The 100 fathom (or 200 metre) contour is of no structural significance, and, as commonly marked on maps, gives the false impression of a highly convolute continental shelf margin. In places it follows broad embayments

* 1 square kilometre equals 0·386 square miles, alternatively 1 square mile equals 2⅗ square kilometres.

far onto the shelf, such as that north of Browse Island. These " bays " are only shallow depressions, however, and have nothing to do with the continental edge. In contrast, the edge of the Sunda Shelf is at about 100m. (or 55 fathoms), and Umbgrove (1929) suggested that this indicated the maximum lowering of the Pleistocene sea-level, rather than the 30–40 fathoms proposed by Daly. The lower level of the Sahul Shelf therefore requires special explanation.

(c) *Topography of the Shelf.*

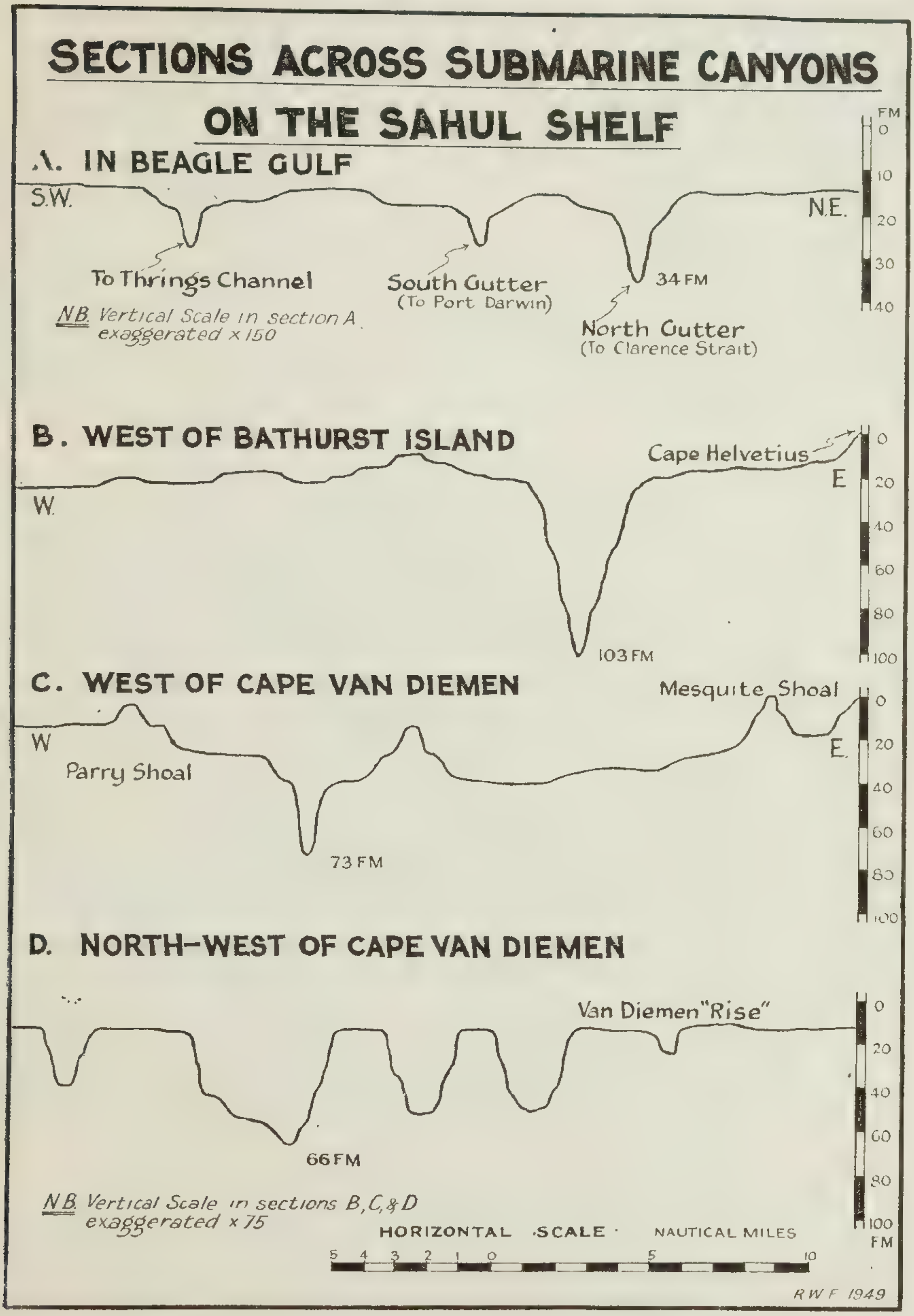
The surface of the Sahul Shelf is far from even. It lacks the smooth contours of the Sunda Shelf, where Molengraaff (1921) worked out the course of the Pleistocene river system (especially of the so-called " Molengraaff River," Dickerson, 1941). On the contrary, the Sahul Shelf is divided into many flat-topped plateaus and terraces, in places with submarine " cuestas," sloping down the shallow basins or depressions. Insufficient sounding data are available for a complete picture, but it appears that there are fairly common terrace levels at about 3–5, 10–15, 25–30, and 55–60 fathoms. The basins range from 10–70 fathoms in depth.



Text Fig. 2.—Sections across the Sahul Shelf. (From Teichert & Fairbridge, 1948.)

Cutting across these flat shelf areas are small, steep-sided canyons, apparently analogous to those found on most other shelf areas. The floors are mostly 30–70 fathoms in depth. The sides are often 100–150 feet high and are quite precipitous in places.

The most striking of these submarine valleys have been disclosed by recent sonic sounding in the approaches to Darwin (see especially charts AUS. 087, 088, 089 and 097). Here, in the area of Beagle Gulf, between Bathurst Island and the mainland, the shelf floor ranges between 10 and 17 fathoms in depth. Cutting across it, however, from south-east to north-west, are the North and South Gutters, which drop to 20 or 30 fathoms, and for long stretches are less than half mile in width. Similar deep " gutters " follow Clarence Strait.



Text Fig. 3.—Sections across submarine canyons on the Sahul Shelf.

The main submarine valley from Beagle Gulf swings around Bathurst Island to run almost due north for more than 80 miles across the shelf (where it is lost through lack of soundings). Its depth averages 50 to 60 fathoms, except in a few places where it is over 100 fathoms. As will appear below, a broad ridge extends north-west from Cape van Diemen and Bathurst Island. This rises also rather uniformly to 10 to 15 fathoms, but is intersected by channels which drop to over 50 fathoms in places. Apsley Strait, between

Melville Island and Bathurst Island, shows soundings down to 29 fathoms, but its possible connection with the deep canyons to the north is almost completely blocked by younger coral reefs. Some of the more westerly of the submarine valleys in Beagle Gulf appear to continue westwards and die out in depths of 60 to 70 fathoms about 100 miles west of Bathurst Island.

Another group of these submarine valleys, or canyons, has been recognised farther west, off the Kimberley coast. One canyon separates Adéle and Churchill Reefs by 60 to 70 fathoms (Teichert and Fairbridge, 1948), and others seem to cross the Sahul Shelf in this region in a north-westerly direction, continuing the trends of the Prince Regent River, Prince Frederick Harbour, etc., but the evidence is less clear for this region, since we lack sonic sounding material for the most part (see British Admiralty Chart 1047 ; and AUS. 094). Further evidence of a drowned river system may be recognised on the Arafura Shelf (Fairbridge, 1951).

The preceding remarks apply in the main to that part of the shelf which is shallower than 55–60 fathoms. Below this level our bathmetric information is still scanty. The possibility of canyons on the outer edge of the shelf cannot be tested yet owing to lack of information. At the 55–60 fathom level is a cuesta-like " step," the edge of the lowest of the abovementioned terraces, where there is a decided change in slope between our " Inner Shelf," an undulating or terraced plateau of no uniform slope, and our " Outer Shelf," which appears to drop down fairly steadily (1 : 400) to the vicinity of the 300 fathom line, where it plunges sharply to the deep ocean floor (Teichert and Fairbridge, 1948). The pattern of this 55 fathom " step " is highly sinuous in plan (see folding map), and thus different in character from the more or less even continental edge at 300 fathoms.

There are also a number of broad transverse undulations on the Sahul Shelf (*s.s.*), three " rises " (ridges of low amplitude) separating two axes of regional depression. One of the latter is open on the Indian Ocean side, but the other, facing the Timor Trough, is completely enclosed. To facilitate reference, names have been given to these gentle warps, and they are from east to west, as follows :

(i) The *van Diemen Rise*, running north-west from Cape van Diemen to the outer edge of the shelf, where it merges with the shoals on which Troubadour, Flinders and Evans reefs are built. Most of this swell is less than 30 or 40 fathoms in depth.

(ii) The *Bonaparte Depression*, an area 100 by 150 miles, named after the Joseph Bonaparte Gulf, between the north Kimberley and the Northern Territory, lies right in the centre of the Sahul Shelf. Most of it is deeper than 50 fathoms, exceeding 70 fathoms, and it is completely surrounded by shallow shelf-floor of 30–40 fathoms depth.*

(iii) The *Londonderry Rise*, running north-west from Cape Londonderry to the Sahul Banks, on the north-east side of which there is a connection of little more than 40 fathoms depth with the north-western end of the van Diemen Rise. The southern half of this swell is very shallow and marked by the extensive Holothuria Banks and Reefs. The northern half is practically all between 40 and 50 fathoms before reaching the shoals of the Sahul Banks.

* Shepard (1948, p. 127) has illustrated this depression.

(iv) *The Browse Depression,* forming a deep enclave in the western end of the Sahul Shelf, lies to the north of Browse Island. It is bounded roughly by the 40 and 50 fathom lines which come very close to the coast near York Sound, but swing out nearly to the shelf edge to the north-west and south-west. To the west, however, it is open and slopes down gently to the 300 fathom line.

(v) The *Leveque Rise,* running north-west from Cape Leveque, is broader and shorter than the other warps, and, unlike them, does not extend to the edge of the Timor Trough, but, after reaching about 100 miles from the coast with depths of less than 40 fathoms, it slopes down gently towards the deeps of the north-eastern Indian Ocean. The group of big reefs and banks between Adèle Island and the Lacepèdes are situated on the inner part of this swell, and the isolated Lynher Reef is on its extremity.

On the Arafura Shelf, beyond the van Diemen Rise, there follows another broad feature, marked by an eastwards sweep of the submarine contours, down to the 100 fathom line, named the *Arafura Depression* (Fairbridge, 1951). North of it comes another ridge which connects the mainland of southern New Guinea with the Aroe Islands, the *Merauke Rise* (van Bemmelen, 1949), and this finally is only separated from the foothills of the Snow Mountains of Dutch New Guinea by a narrow trough, the western extension of the Papuan Geosyncline, which may be called the *Snow Mountains Trough.*

To the east of Arnhem Land, the Gulf of Carpentaria occupies a very broad depression (averaging 30–35 fathoms), comparable in some ways to the Bonaparte Depression further west, or even, as Wade (1924) suggested, with the Desert Basin on the mainland. The north-western limits of this *Carpentaria Depression* are partly cut off by a swell of under 30 fathoms which runs north-east from Wessel Island and Cape Arnhem, the *Wessel Rise.*

In the other direction, on the Rowley Shelf, beyond the Leveque Rise, there is another major depression, the *Rowley Depression,* in the outer centre of which rise the Rowley Atolls. On the coast side lies Broome and the structural depression of the Desert Basin. Closing round its western side comes a broad rise, the *Dampier Rise,* from the Dampier Archipelago there. Only a narrow shelf connects finally to North-west Cape.

(d) *Interpretation of Bathymetric evidence* :

Molengraaff (1921) interpreted the Sahul Shelf as a continental marginal area which had been completely peneplaned by the end of the Pleistocene. However, the shelf has a terraced character. The terraces at 3–5, 10–15, 25–30 and 55–60 fathoms may be simply explained by erosion during eustatic lowerings of sea-level during the Pleistocene, as noted already in the Abrolhos and Peron regions of Western Australia (Fairbridge, 1950b), and by others in many parts of the world (Daly, 1934 ; Zeuner, 1945).

Evidence of the mid-Recent eustatic emergence of 10 feet is also widespread along the shores of the Kimberley and Northern Territory (Cadell, 1899 ; Brown, 1906 ; Woolnough, 1912 ; Jensen, 1914 ; Basedow, 1916, 1917), as well as on the major off-lying islands (Teichert & Fairbridge, 1948), and on adjacent East Indian islands (Kuenen, 1933 ; Umbgrove, 1947b). These indications of uniform submergences and emergences lead to the conclusion

that the inner part of the shelf and mainland shores have been fairly stable geologically, at least during the latter part of the Quaternary. On the other hand, evidence from Timor suggested great instability continuing right up till Recent times (Molengraaff, 1913).

The inner part of the shelf appears as a drowned landscape, which may well have been developed during arid cycles of erosion. It was a plateau, terrace and plain country in which the streams were fairly deeply incised, the down-cutting having been revived in stages to present a step-like cross-section to the canyons. The surface, in short, is just like that of many parts of the adjacent Kimberley and Northern Territory today.

In certain areas, however, such as in the submerged ridge north-west of Cape Van Diemen, the streams appear to have cut down canyons of antecedent character, since they are deeper in the centre of the ridge than either north or south of it. Parts of these shelf canyons, being over 100 fathoms in depth, cannot be explained by the normal eustatic processes. Some Quaternary tectonic movement may have occurred here.

The terraced (inner) section of the shelf comes to an end at the 55–60 fathom " step ", which thus seems to be a feature of rather special significance. This level is often regarded as the extreme limit of eustatic lowering of sea-level during the Pleistocene. The steady outward slope from the "step" down to the continental edge suggests another explanation for the outer shelf, perhaps tectonic subsidence. It is significant that isolated coral reefs rise respectively from near the edge of the 55–60 fathom " step " and near the outer (300 fathom) edge. For discussion of this problem see Section VI.

The difference between the Sahul Shelf and the Sunda Shelf is possibly due in part to climatic factors. Large tropical rivers like the Solo, Barito and Moesi are continuously adding vast quantities of sediment to the Sunda Shelf, while the hinterland of the Sahul Shelf is semi-arid, and the rivers are consequently seasonal and small compared with those of Java, Borneo, and Sumatra. The tremendous volume of these Sunda Shelf sediments has been stressed by Tercier (1939) ; for example the Solo River of Java carries approximately eight times the sediment of the Rhine. The nature and provenance of the Sunda sediments has recently been described by van Baren and Kiel (1950).

It is suggested, therefore, that excessive sedimentation is quickly obscuring signs of Pleistocene terracing and stream revival in the Sunda Shelf, while relatively slow sedimentation on the Sahul Shelf leaves the angular topography still relatively bare. It is possible that greater exposure to powerful tides and currents on the Sahul Shelf is a contributing factor in keeping it clear, as in the case of Adèle Reef (Teichert and Fairbridge, 1948).

The concept of the Sahul Shelf as dry land at times during the Pleistocene is far from new. From the zoogeographic point of view Wallace (1869) found evidence of Pleistocene migration across the Torres Straits (where an emergence of less than 10 fathoms would provide a bridge from New Guinea to Australia), but while there was a ready interchange of the more mobile creatures across the Timor Trough (1,000 fathoms deep), there was always maintained some sort of sea barrier here, even though it must at times have been very narrow.

Without apparently giving much thought to the geological implications of the hypothesis, Rensch (1936) postulated a Pleistocene land-bridge across the Timor Trough to account for the zoogeographical relationships. Mayr

(1944a), after exhaustive investigations, came to the conclusion that Wallace was right, and that despite the well-recognised Glacial lowering of sea-level, the depth of the Timor Trough would long have maintained a certain barrier, which permitted the passage of only specialised classes of migrants. For earlier times he follows Kuenen (1935, p.107) in believing that there were continental connections between Australia and the East Indies up till the early Eocene, but that the zoogeographic evidence demonstrates a complete separation between these two from Eocene till the early Pleistocene.

Mayr's special study, the avifauna of the East Indies and adjacent areas, also provided the interesting conclusion that since most of the recent arrivals in Australia from Timor were grassland birds, there must have been arid, savannah-type of country on the Sahul Shelf during the periods of migration (Mayr, 1944b.)

Support for this idea is the climatological conclusion of C. F. Brooks (in a personal communication, cited by Mayr, 1944b), who observed: "By closing Torres Straits and making most of the Sahul Shelf dry land, the climate in the southern hemisphere winter would be very dry, and opportunities for rainfall in the southern hemisphere summer would be reduced. The North-West monsoon would be drier than it is today, after passing over the higher mountains and more continuous land of Pleistocene times. I should think that the summer climate in the thus protected area west of New Guinea and north-west Australia might well have been arid........" Quite recently Gentilli (1949) has prepared a series of palaeoclimatic maps of Australia for the Pleistocene, which clearly illustrate this widespread desiccation at certain stages.

It is apparent also that for long periods during the Pleistocene, the great transverse "rises" recognised in the regional bathymetry of the Sahul Shelf would have been emergent promontories, thus extending the periods during which migration would be favoured beyond the brief limits of the extremely low sea-levels.

Most of the depressions on the other hand, with their broad shallow bays at such times, would seem to favour the development of extensive mangrove swamps, while the Bonaparte Depression may have been reduced to a swampy lake whenever the sea-level was more than 30-40 fathoms below the present.

III. CORAL REEFS AND SEDIMENTS OF THE SHELF.

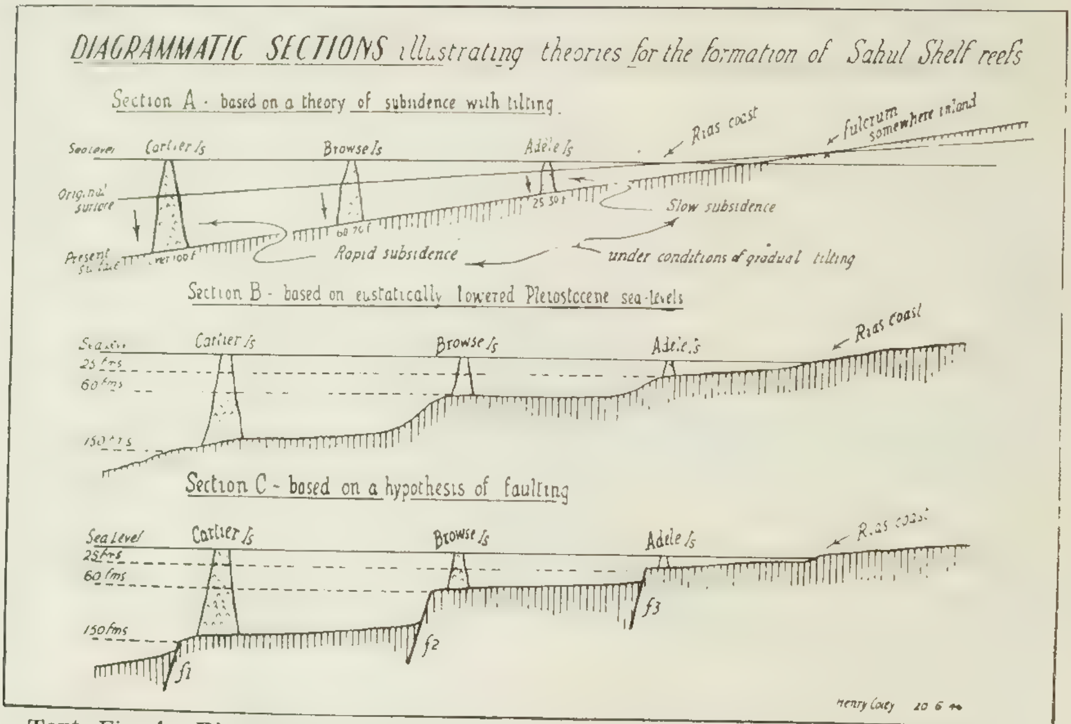
Both coral reef accumulations and normal sedimentation contribute towards the covering of superficial material on the surface of the shelf.

(a) *Coral Reefs and other islands.*

The distribution and significance of the coral reefs have been discussed by Teichert and Fairbridge (1948), and further in their regional setting (Fairbridge, 1950b).

There is firstly a disconnected row of reef platforms and atolls arising from fairly deep water (down to nearly 300 fathoms) along the outer edge of the shelf (including Scott, Seringapatam, Ashmore, Sahul Bank, Troubadour, etc.), which in places forms an ill-defined barrier. Scattered intermediate reefs rising from levels between 40 and 60 fathoms (including Cartier, Browse, etc.), and in shallow water near the coast are the large platform and fringing reefs (including Lacepèdes, Adèle, Holothuria, etc.).

Those reefs nearest the coast are controlled by the contours of the basement (Pre-Cambrian). In some that basement is showing and in others it is even predominant, so that the coral is reduced to the status of a discontinuous fringe. The intermediate row of reefs grow up from near the 55 fathom "step," which may mark the limit of the lowest Pleistocene sea-level. The outermost row, however, rising as it does from deep water, well below the growth range of normal, living corals, suggests that slow subsidence has been taking place here, either by step-faulting or by a slow tilting towards the exterior. There is no sign of any drowned volcanic stocks (such as Hesse's "Guyots," or sea mounts), or other basement elevations, which makes the occurrence of perfect atolls here particularly interesting.



Text Fig 4.—Diagrammatic sections illustrating theories for the formation of the Sahul Shelf reefs. (From Teichert & Fairbridge, 1948.)

The "continental" islands, which are also mainly surrounded by fringing coral, occur chiefly in the Buccaneer Archipelago, off the north Kimberley coast, and are composed of Pre-Cambrian rocks. The large islands off the Northern Territory, including Bathurst and Melville Islands, are mainly Tertiary and Cretaceous on a Pre-Cambrian basement (*see* also Section V.). With the sole exception of the Aroes, however, there are no continental islands at any great distance from the shores of the mainland.

(b) *The Sediments.*

The size of the Sahul Shelf, and its geographical relationships, should make it a particularly interesting area for the study of sediments. The rivers from the semi-arid interior and sub-tropical margins of the continent are strictly seasonal in character. We may expect, therefore, the outer parts of the shelf, 100 to 200 miles from land, to have a very slow rate of terrigenous sedimentation, but sediments from other sources should be relatively important.

One of the earliest references to the sediments of the shelf comes from Captain Heywood, R.N., who, in 1801, referring to the area roughly between the Sahul Banks and the Holothuria Banks, described the irregular way in which coral shoals rose up steeply from the general level of the shelf, "close

to them the bottom was generally coarse sand and bits of shells ; farther off, fine sand ; and when clear altogether, a sort of green sandy ooze " (*see* Horsburgh, 1811). Stokes (1846, vol. II, p. 119) in the same area found in the shallows " coral with bits of ironstone mixed with sand ; whilst in the greater depth, it was green sandy mud." The " ironstone " referred to sounds very much like laterite, which is such a characteristic feature of subaerial weathering on the continent.

From the general evidence of Admiralty soundings these descriptions are widely applicable. Many subsequent naval surveyors have referred to the sediments, in greater detail, but in the same general terms. Coral sand and debris is marked at many points on the charts in depths from sea-level down to 100 fathoms. Actual living coral is reported from quite considerable depths ; in Sunday Strait, Stokes (1846, vol. I, p. 185) noted a particularly beautiful fragment from 30 fathoms. Farther out there are clearly many submerged reef patches which do not come yet within many fathoms of the surface. Nevertheless, by far the greatest area is floored with " mud " of one sort or another.

No systematic sampling has been carried out on the body of the Sahul Shelf, but on the Arafura Shelf we have the advantage of a series of dredgings made by the " *Challenger* " Expedition (1872–76), between the Torres Straits and Aroe (stations 186 to 190, *see* Murray and Renard, 1891, chart 31). The data show that near the coral islands in the Torres Straits, the sediments are mainly coral sands with foraminifera. Three soundings right out on the shelf (188–190) show " green, sandy mud " or " green mud." It is perhaps worth summarising the material on these three stations, as indicating a typical cross-section of the shelf deposits (where they are well clear of the coral reefs) :—

Station 188 in 28 fathoms .... (9°59′S., 139°42′E.) Green, shelly sandy mud : 38% $CaCO_3$ (15% foraminifera and 23% other shells) ; 3% siliceous organisms ; 45% quartz, glauconite, felspar, hornblende, etc. ; 13% " fine washings."

Station 189 in 28 fathoms .... (9°36′S., 137°50′E.) Green mud : 31% $CaCO_3$ (10% foraminifera, 21% other shells) ; 3% siliceous organisms ; 25% quartz, glauconite, mica, tourmaline, zircon ; 40% " fine washings."

Station 190 in 49 fathoms .... (8°56′S., 136°05′E.) Green mud : 23% $CaCO_3$ (4% foraminifera, 19% other shells) ; 2% siliceous organisms ; 50% quartz, glauconite, felspar ; 25% " fine washings."

Of these analyses the " fine washings," as explained by Murray and Renard (1891, p. 24–5), refer mainly to insoluble material of fine nature, which was largely made up of minute clay and heavy mineral grains. Some of this material may well be wind-borne to the Sahul Shelf, since the south-east winds from the continent of Australia are a very persistent feature. As many authorities have shown, such as off the west coast of Africa, aeolian constituents may go to make up a considerable fraction of the whole sediment.

The high calcium carbonate percentages are, of course, to be expected and the green coloration is mainly due to the glauconite. The latter is a highly significant mineral in sedimentation : it suggests a shelf deposit of terrigenous origin—being common off desert and semi-arid shores, where

other terrigenous deposits do not mask its development ; in stratigraphy it is taken to indicate very slow accumulation and even disconformities (Hadding, 1932).*

The careful surveys of the *Snellius* Expedition in the East Indies were carried right across the Timor Trough up to the edge of the Sahul and Arafura Shelves in many places, and the results of the bottom sample analyses have appeared recently (Kuenen and Neeb, 1943). At several places right on the edge of the shelf are coral muds ranging from 95 to 99 per cent. $CaCO_3$. The coarse fractions, strictly coral *sands*, are relatively important in the vicinity of the Sahul Banks proper, but since none of these reefs are awash today, the sediments must date back to before the recent " drowning " by subsidence, or even to the Pleistocene period when they were exposed periodically to wave action.

As regards the deep-water sediments, off the edge of the Sahul Shelf, towards the Timor Trough and the Wharton Deep (North Australia Basin), the Admiralty charts show extensive developments of globigerina ooze, and blue terrigenous mud in the direction of Timor. Pteropod ooze is noted off the southern tip of Tanimbar and radiolarian ooze is recorded below 1,000 fathoms in the middle of the Timor Trough south of Sermata. Right out in the Wharton Deep, below 3,000 fathoms, one finds the usual red mud.

While the globigerina ooze belt ranges from the edge of the shelf down to about 1,000 fathoms in the centre of the trough, from there on to the shores of Timor is all a belt of terrigenous mud, which clearly came from the north (Kuenen and Neeb, 1943). Of particular interest is the recognition of two special belts of terrigenous origin, superimposed on the globigerina ooze belt, which appear in contrast to come from the south and east, i.e., the shelf region. These respectively run from near Troubadour Reef to south of Tanimbar and from there right round the Aroe Basin to beyond the Bomberai in Dutch New Guinea. The first is marked by the appearance of minerals of igneous and metamorphic origin, notably epidote, and the second by quartz grains apparently derived from some dominantly sandy formation. The old igneous province to the south appears to be the extension of Archaeozoic rocks in the van Diemen Rise, and the sandy province in the east probably the Proterozoic-Mesozoic sandstones extending from Arnhem Land on the Arafura Shelf. Their distribution can best be explained as deltaic deposits of the Pleistocene streams described above.

The deepwater sediments of the East Indies (*see* Kuenen, 1939 ; Kuenen and Neeb, 1943 ; and Tercier, 1939) are completely different from those of the Australian area. Furthermore they are types which do not seem to occur at any time throughout the sedimentary evolution of northern Australia. The conclusion, therefore, would be that the Sahul-North Australian region has always been of shelf, shallow basin, or continental nature since the Pre-Cambrian. That this shelf has varied periodically from the true continental (emergent) to the epicontinental (with low shores and reduced sedimentation),

* The source of the glauconite has been traced to many substances, foraminiferal tests (Murray and Renard, 1891, pp. 378–391), coprolites and a variety of minerals. Galliher (1936) demonstrated a continuous gradation from biotite to glauconite, from biotite sands near the shore to pure glauconite mud near the 100 fathom line. Glauconite however forms also where there are no great quantities of micas (Hendriks and Ross, 1941, and others). Takahashi (1939, p. 503), concluded that glauconite was only formed under marine conditions where the summer water temperature was not less than 15° C. with normal salinity ; the process was one of submarine metamorphism under anaerobic or reducing conditions, generally associated with iron sulphides. Subsequent reworking may lead to concentration with other heavy mineral sands. The glauconite may originate from a variety of original minerals : felspar, mica, pyroxene, or from similar clayey material filling the tests of organisms such as foraminifera and radiolaria or replacing faecal pellets. The presence of organic matter thus favours the process, which involves the hydration of silica followed by the absorption of bases and the loss of alumina.

to the paralic (with higher relief and increased sedimentation), should appear from the geological discussions to follow. In these characteristics it has something in common with the Sunda Shelf, though the borders of the latter appear to be structurally much more active.

Tercier (1939) has emphasised that the difference between the Sunda and Sahul Shelves is more one of climate than of depth. The Sunda Shelf, on the one hand, is entirely within the equatorial belt and as noted above there is fine sedimentation on a tremendous scale. Against this, the sediment brought down by north Australian rivers to the Sahul Shelf is almost negligible. Only in the north-east are comparable conditions found, where the rivers from the Snow Mountains of Dutch New Guinea bring down plentiful sediment to the northern side of the Arafura Shelf. The very fine reddish white clays of southern Dutch New Guinea, which are found as far south as Merauke (Heldring, 1910) and even in Aroe, appear to be from this source (Sperling, 1936). The relative absence of alluvial plains in northern Australia is in striking contrast to the broad tracts of southern New Guinea and the coastal lands of Java, Sumatra and Borneo which face the Sunda Shelf. In contrast to the Sahul Shelf, there is extremely little glauconite anywhere in East Indian sediments (Molengraaff, 1929, p. 991).

Fine terrigenous sedimentation on the Sunda Shelf thus contrasts with coarser material on the Sahul Shelf. The conditions favour coral reef growth on the latter, and also inhibit it on the former except in places kept clear by currents (Umbgrove, 1947b). Fringing reefs are almost unknown along the mainland shores of the Sunda Shelf, but are common along the north Australian coasts, except in those places where loose sands, river mouths and mangrove present unfavourable habitats.

Quaternary events in the region do not disclose any indication of sedimentation on the Sahul Shelf having been much faster, except during the short stages of rising sea-level associated with deglaciation. Slow sedimentation seems to have been the rule for long periods in the past. In places there may be only a thin veneer of sediments resting on a Pre-Cambrian basement.

Tercier takes the Sahul Shelf (along with Yucatan, Florida and Bahama Shelves) as the type area of his " neritic sedimentation of epicontinental platforms," which are characterised by limestone, marls and calcareous shales, with very reduced amounts of terrigenous material. Against this he classifies the Sunda Shelf (along with the northern coast of the Gulf of Mexico) as " neritic sedimentation of paralic platforms," characterised by very thick terrigenous deposits, alternating between marine, estuarine and continental facies, including coal measures.

One factor, however, seems to have been rather neglected by Tercier: that of the siliceous and heavy materials on the epicontinental platforms. These components are insoluble and fairly coarse grained. They are common and often predominant in northern Australian sediments. In areas of strong currents they are left behind when fine material is swept away; on land they are concentrated by the leaching out of soluble fractions and by wind. In this way they would appear to be of great longevity, being reworked and redeposited again and again through geological time. With a shallow shelf and a low continental shore, eustatic oscillation of the sea-level seems to be the most important factor in this cycle.

IV. GEOLOGY OF THE ADJACENT MAINLAND.

Nothing is known directly of the geology of the Sahul Shelf, since no continental rocks are exposed on it. So we must look for analogies on the adjacent mainland. Structurally the northern parts of Australia consist of a number of major tectonic blocks, which are marginal to the great Pre-Cambrian Shield, and show alternating positive and negative tendencies to rise or sink during post-Archaean times. Only the early Pre-Cambrian rocks of this region are extensively folded, metamorphosed, and intruded by granites.

All subsequent sediments are flat-lying or gently folded, and hardly at all metamorphosed. The folding is restricted to narrow, active belts associated with the margins of the blocks, which are generally bounded by major normal faults, monoclines or broad warps. Post-Archaean diastrophism is thus mainly epeirogenic, with restricted taphrogeny (fragmentation) and fault-folding of Saxonian type. In the basins sediments are up to 20,000 feet or so, while on the rising blocks Wade (1924) has allowed not more than 500 feet for the entire sedimentary succession; they are, he says, parts of "the oldest and most persistent land areas in the world."

It seems desirable to identify the individual structural units of the mainland, and, from west to east, they are :—

- (a) Pilbara Block.
- (b) Desert (Canning) Basin.
- (c) North Kimberley Block.
- (d) East Kimberley Basins.
- (e) Western (Daly-Victoria) Rivers Basin.
- (f) Arnhem Land Block.

Owing to serious gaps in our geological knowledge of these areas, boundaries are only poorly defined, and there is room for much further study.

(a) *Pilbara Block.*

Of mainly Pre-Cambrian rocks, it forms the northern end of the Great West Australian Plateau, and its southern boundaries are thus somewhat arbitrary (Jutson, 1934). It consists of a high but deeply dissected plateau, dropping to a narrow coastal plain and to the low Desert Basin (q.v.) in the north-east.

The basement of ancient Pre-Cambrian metamorphic rocks is mainly covered by flat-lying or undulating Nullagine sediments, generally considered to be late Proterozoic. Trends in the older rocks on the north-west (coastal) side are N.E.-S.W., while to the south-west and north-east they are N.W.-S.E. (Hills, 1946). These older trends are also reflected in the gentle folds and block-fault patterns of the Nullagine physiography. The Nullagine structures appear to be early Caledonian, but were modified by warping and faulting in post-Permian and even late Tertiary times.

(b) *Desert (Canning) Basin.*

A roughly rectangular unit, bounded by the Eighty-Mile Beach on the north-west, and covering some 140,000 square miles, the Desert (or Canning) Basin is filled mainly with Permian and older Palaeozoic sediments (Teichert, 1947, 1950; Guppy and Opik, 1950; Reeves, 1951), which appear to have accumulated to a thickness of over 20,000 feet in a deep trough coinciding with the Fitzroy Valley and lying on the south-east of the North Kimberley

Block. Post-Permian marine sediments are known along the coast, where Jurassic sandstones are found in bores (Teichert, 1939, 1940, 1947). Other sandstones near the coast are Cretaceous (Brunnschweiler, 1951) and there may be a little Tertiary, but diagnostic fossils have not been found. The beds of the Desert Basin are folded and upturned along the north-eastern margin, thus showing N.W.-S.E. strikes, associated with the secondary folding and faulting (Wade, 1924, 1936). The initial subsidence of the basin was in early Palaeozoic times, culminating at the end of the Permian and later periodically revived, movements which were probably paralleled by regional upwarps of the adjacent Pre-Cambrian massifs.

(c) *North Kimberley Block.*

This is another rectangular-shaped block, but forming a plateau of about 90,000 square miles, the sides trending N.W. and N.E. It is capped by gently undulating sediments, mainly sandstones, intercalated by basalts and generally taken to be Nullagine in age (Clarke, 1938). The basalts are of "plateau" type (Edwards, 1942). The youngest of the basalts is regarded as of Lower Cambrian age (Teichert, 1947).

Older, highly folded, rocks of Mosquito Creek and Warrawoona age underlie the Nullagine rocks at no great depth and outcrop along the margins of the block in the Leopold Range and extend north-west to the Yampi Sound area, where the regional strike varies from W.N.W.-E.S.E. to N.W.-S.E. The same trends may be followed out on the continental shelf beyond Cape Leveque (Wade, 1936 ; Teichert and Fairbridge, 1948), in what we are now calling the "Leveque Rise."

The overlying Nullagine rocks are subject to a regional jointing in N.W.-S.E. and N.E.-S.W. lines, as shown by the stream patterns and by margins of the block. Epeirogenic upwarping has continued since before Nullagine times, movement occurring especially in late Cambrian and post-Permian tmes and extending even to late Tertiary times (Hills, 1946). Jutson (1934) describes the North Kimberley as an old peneplain in the course of vigorous youthful dissection by a great number of streams (there is a mean rainfall of 20–60 inches). The coast is very precipitous and it was compared already by Gregory (1913, p. 347) with ria coasts. Most fiord-like is the Prince Regent River, which is 240 feet deep not far from its mouth, but then the floor rises again to a threshold ; such a feature, Gregory contended, prevents it being called a true ria coast, but this may well represent a subsequent, sedimentary accumulation of no genetic significance.

There is a fundamental difference between the north-west and north-east coasts of this block. The former is a ria coast with numerous off-lying islands and reefs which grow up presumably from submerged continental ridges, including the Leveque and Londonderry Rises. The north-east coast has an almost rectilinear trend (N.W.-S.E.), no rias, no offshore islands, no reefs, and drops off steeply into quite deep water. It thus appears to be faulted, and the line may be called the "Cambridge Fault" after Cambridge Gulf, which is cut off by it. The same fault appears to continue to the south-east from the mouth of Cambridge Gulf, separating the North Kimberley Pre-Cambrian rocks from the Permian of the Bonaparte Gulf region (Dr. Frank Reeves : personal communication).

(d) *The East Kimberley Basins.*

Abutting against the eastern margins of the North Kimberley Block is a complex shatter zone of severely faulted basins and horsts. Maitland (1919) depicted only a single "Gulf Basin" here, but Matheson and Teichert (1948) distinguished several more. Reeves (1951) called the main one the "Bonaparte Gulf Basin."* These basins contain probably 5,000 feet of Nullagine and Cambrian sediments with basalts (see Edwards and Clarke, 1940), and are followed uncomformably by 12,000 feet of Devonian, Carboniferous and Permian.

The structural history appears to be somewhat similar to that of the Desert Basin but is more complex. The movements were probably most active in the late Cambrian, post-Permian and later Tertiary to Recent times. Even late Tertiary lake deposits have been deformed (Matheson and Teichert, 1948), which provides an explanation for the youthful physiography of this belt. Its youthful subsidences appear to be connected with the downwarping of the Bonaparte Depression lying to the north.

(e) *Western (Daly-Victoria) Rivers Basin.*

This is an imperfectly defined region of about 80,000 square miles which occupies the north-western part of the Northern Territory of Australia.† Structurally, it is a broad shallow basin, which may be related to the East Kimberley Basins in the same way as the centre of the Desert Basin is to the complex north-eastern belt of Permian and Devonian in the Fitzroy belt. It is underlain by older Pre-Cambrian (Mosquito Creek) metamorphic rocks granites which emerge to form its eastern boundary, outcropping in the east along the Darwin-Katherine watershed, and also appearing in a belt parallel to the coast 20–30 miles inland. The "grain" is essentially N.W.-S.E. to N.N.W.-S.S.E.

The centre of the basin is occupied by gently undulating areas of Cambrian and Nullagine (Woolnough, 1912). On these are isolated buttes and small plateaus of flat-lying Mesozoic beds known as "Pleateau Sandstones." They are generally not more than 50 to 100 feet in thickness. At Buldiva they were found to contain *Otozamites* and so regarded as Jurassic. From foramnifera Miss I. Crespin (pers. communication) believes that they are Lower Cretaceous.‡

On the seaward side of this basin, beyond its north-west border of early Pre-Cambrian, there is a 2,000 square mile belt of Permian and possibly Carboniferous (Brown, 1895; Woolnough, 1912; Basedow, 1916). They are generally flat-lying, but locally have gentle dips and strike E.-W. or N.E.-S.W. Farther north-east from Anson Bay to Darwin the coastal stretch is occupied by an area of marine Cretaceous rocks (Brown, 1895, 1906). Recent work by Noakes (1949) indicates that these overlie continental sandstones inland.

* Now described in more detail by L. C. Noakes, A. A. Opik and Irene Crespin: "Bonaparte Gulf Basin, North Western Australia. A stratigraphic summary with special reference to the Gondwana System." Congr. Geol. Internat. (XIX., Alger, 1952).

† The name "Western Rivers District" was used by Basedow (1916); it is not a political or historic unit, but covers the Daly-Victoria basins quite appropriately).

‡ They have named "Mullaman Group" by Noakes (1949); *see* also Noakes, Opik and Crespin: "Bonaparte Gulf Basin . . . ." (*vide supra*).

(f) *Arnhem Land Block.*

Covering more than 70,000 square miles, this block is bounded by the Darwin-Pine Creek-Katherine line, the Roper River, the Gulf of Carpentaria and the Arafura Sea. It is a great dissected dome, consisting of an ancient peneplaned block, overlain by a thin veneer of late Proterozoic (Nullagine) and Mesozoic sediments (Jurassic, of Voisey, 1939) which was regionally up-warped in Tertiary times. While the bedding is only gently undulating, in the north-coastal parts there is marginal block-faulting, with monoclinal folds and steep dips (Brown, 1908; Jensen, 1914). Faulted blocks trending N.E. and dipping 2–5° N.W. condition the orientation of Wessel Island and vicinity, and Jensen mentions a secondary set of faults here, trending N.W.–S.E. The highest parts are probably fault-bounded horsts (Jensen and Playford, 1913). Out on the continental shelf the north-west trend of the Pine Creek line appears to be extended in the van Diemen Rise.

Lying beyond the Arnhem Land Block to the east comes the broad depression of Carpentaria. This may be an old Pre-Cambrian block (Jensen's "Carpentaria Massif," 1923; Hills' "Carpentaria Nucleus," 1946), but it was repeatedly flooded by epeiric seas during the late Palaeozoic, Cretaceous and Tertiary times. Heldring (1910) believes the entire region from southern New Guinea to the Gulf of Carpentaria, west of his "Torres Strait Horst" and east of the Aroes, forms an immense elliptical "senkungsfeld" today. Thus it has now begun to assume the role of a shallow basin—an interesting reversal in character.

(g) *Aroe Islands.*

Situated 400 miles out on the Arafura Shelf north of Arnhem Land, the Aroes represent the only continental shelf islands so far out. Wichmann (1887) regarded them as an outermost East Indian arc, a view supported by Koto, but subsequently all authors have agreed that they belong structurally to the continent (Gregory, 1924; Fairbridge, 1951).

The islands consist of a Miocene-Pliocene limestone plateau, much jointed and dismembered into blocks and recemented by a cover of young coral limestone (Verbeek, 1908, p. 475; Gregory, 1924; Zwierzicki, 1927, p. 312; Kuenen, 1933). The Mio-Pliocene beds are very gently undulating (Tayama, 1936). Coarse grains of terrigenous minerals in the sediments indicate that the basement is not far off and at Kampoeng Sia (Serani), Tissot van Patot (1908) reported granite*, which may be compared with a similar boss of granite at Mabaduan on the south coast of New Guinea (Gibb Maitland, 1892; David, 1932, fig. 8), where the shallow basement is recognised from oil-well drilling.

The age of these two granites has not been determined, but since there appears to be no significant tectonic boundary separating them from the early Pre-Cambrian crystalline rocks of the Northern Territory and North Queensland, it seems safer to accept their Pre-Cambrian age (Fairbridge, 1950c) than to assume completely hypothetical Caledonian and Hercynian orogenic belts across this area as done by Kölbel (1945), Stille (1945) and Glaessner (1950).

Regarding the Quaternary history of Aroe, there are several significant features. First, there is the essentially "Australian" character of the Aroe fauna and flora. Earl (1845) believed that the presence of the kangaroo on

* Recently Van Bemmelen (1949) quoted a personal communication from A. Heim to the effect that only coarse sands were found at this spot.

Aroe showed an original connection with Australia and New Guinea. Further zoogeographic evidence leading to the same conclusion was gathered by many authorities (*see* Wallace, 1857 ; Longman, 1924 ; Sperling, 1936 ; Keble, 1947). Such land connections would automatically have come about during low Pleistocene sea-levels.

Secondly, there are no emerged Pleistocene coral-reefs on Aroe (Kuenen, 1933). If stable conditions had existed, one would expect to find such reefs at the appropriate heights corresponding to the various high eustatic sea-levels of the Pleistocene. It would seem that the islands had not yet been elevated.

Thirdly, there are the peculiar " soengeis " (Malay : river), which are deep channels crossing the islands from side to side (*see* text fig. 5). Wallace (1857, p. 479) suggested that they were remnants of drowned stream beds, from rivers that formerly flowed across the shelf from the Snow Mountains of New Guinea. From the angular pattern of the soengeis, van Hoëvell (1889), Verbeek (1908), Merton (1910), Brouwer (1917), van Straelen (1933), and others have concluded that the initial lines of weakness were due to jointing or even faulting. Study by the writer of recent air photographs confirms the joint patterns but no fault displacements were observed. Similar jointed structures are crossed by antecedent streams (Merauke and Digoel) in southern New Guinea (Heldring, 1910), and there seems little doubt that Wallace was essentially right in the case of the Aroe soengeis. It is doubtful, however, if these antecedent streams would have come from so far as the Snow Mountains, for the soengeis are hardly wide enough to represent big valleys.

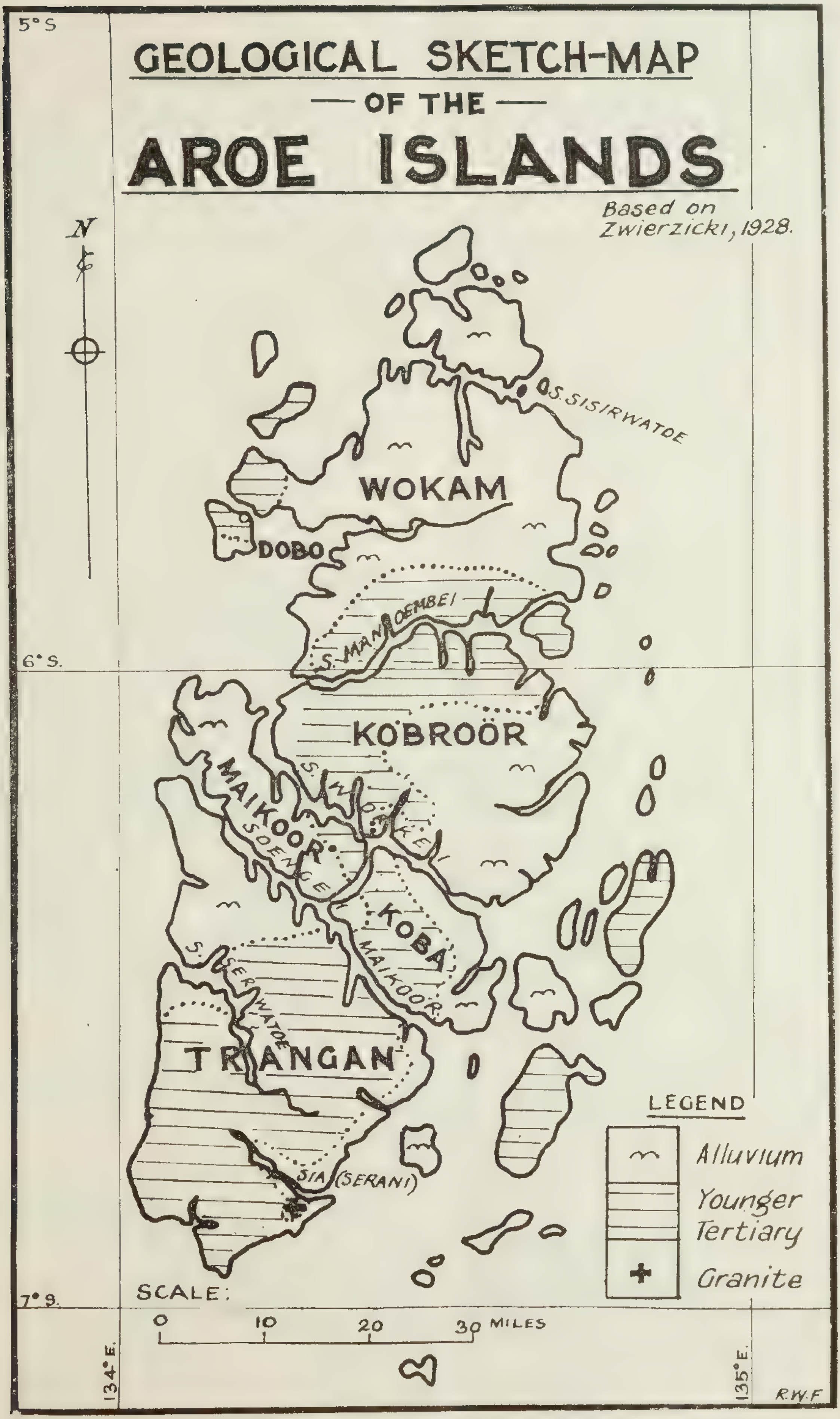
From this Quaternary material one may conclude that the Aroe Islands represent the summit of a broad ridge (an extension of the Oriomo axis of southern New Guinea, Carey, 1938), which was slowly arched up from the Arafura Shelf towards the close of the Pleistocene, thus producing rapid downcutting of stream-beds which were maintained during the upwarp. The islands were well elevated by mid-Recent " Atlantic " times, so that they formed a refuge for Late Pleistocene faunas which would otherwise have been drowned at this time when the sea-level rose to +10 feet. At this stage the former stream valleys were completely cut off and inundated, forming the soengeis seen today. Elevation may still be in progress.

It is apparent that the Aroe Islands belong structurally to Australia, although they differ from the major units of northern Australia in view of their late upwarp. Their basement, however, appears to be similar to, say, that of Arnhem Land, and their Quaternary record provides an explanation of the features on the outer part of the Sahul Shelf. The drowned canyons of the Van Diemen Rise find an obvious analogy in the soengeis of Aroe. Above all it is clear that the outer margins of the shelf facing the East Indies has suffered pronounced movements during quite late geological times.

V. RELATIONSHIP OF AUSTRALIA TO THE EAST INDIAN ARCS.

(a) *Gravity Anomalies.*

Although no thorough gravimetric study has been made of the Sahul Shelf, Vening-Meinesz (in the Dutch submarine surveys of the East Indies) made an examination of the adjoining Timor Trough and in a few places extended it onto the shelf. This is enough to show that on the Sahul Shelf there is generally a regional isostatic anomaly of less than plus 50 milligals, which is in every way comparable to that of the Sunda Shelf.



Text Fig. 5.—Geological sketch-map of the Aroe Islands.

The Timor Trough anomalies are quite characteristic of continental margins (Vening-Meinesz, 1934). While the bathymetric curve slopes down from the shelf edge to the floor of the Timor Trough, the gravity anomaly curve maintains a high course (mostly on the positive side) for a considerable distance beyond the shelf edge before it plunges to the negative. Actually it reaches its lowest at a point roughly coinciding with the south coast of Timor (over minus 100 milligals), after which it rises steeply again to a notable positive anomaly in the interior of the Inner Banda Arc. It gives the impression that the continental structure and material of the Sahul Shelf continue out beyond the actual edge of the shelf.

In reviewing the evidence of the belt of negative anomalies coincident with the Outer Banda Arc and its " foredeep," the Timor Trough, Kuenen (1935, p. 62) says :

> " The Australian Continent influences the direction of the line of negative anomalies, but hardly in character or intensity. There is nothing in the gravity field to indicate either that the Australian block was forced up against the arcs, or that the Outer Banda Arc was originally a regular curve and was subsequently moulded up against the already existing shape of the continent."

Further discussion is to be found in his earlier contribution to Vening-Meinesz' work (1934, p. 189, *et seq.*). Many tectonic theories on the East Indies have in the past ranged from a regional " squeezing " movement to to a fully-fledged continental drift of Australia against the Lesser Sunda Arcs, but Vening-Meinesz' evidence would oppose such concepts. On the other hand, the structure of Aroe (lying as it does on the continental shelf) shows a slightly arcuate trend, paralleling the Banda Arcs, thus implying some mutual influence (Brouwer, 1920). Furthermore, observations regarding the depressed (300 fathom) continental edge, and the local rises paralleling the Timor Trough in the Sahul Bank—Cartier Reef section—suggest that such influences are not restricted merely to the Arafura Shelf, but extend all along the Sahul Shelf.

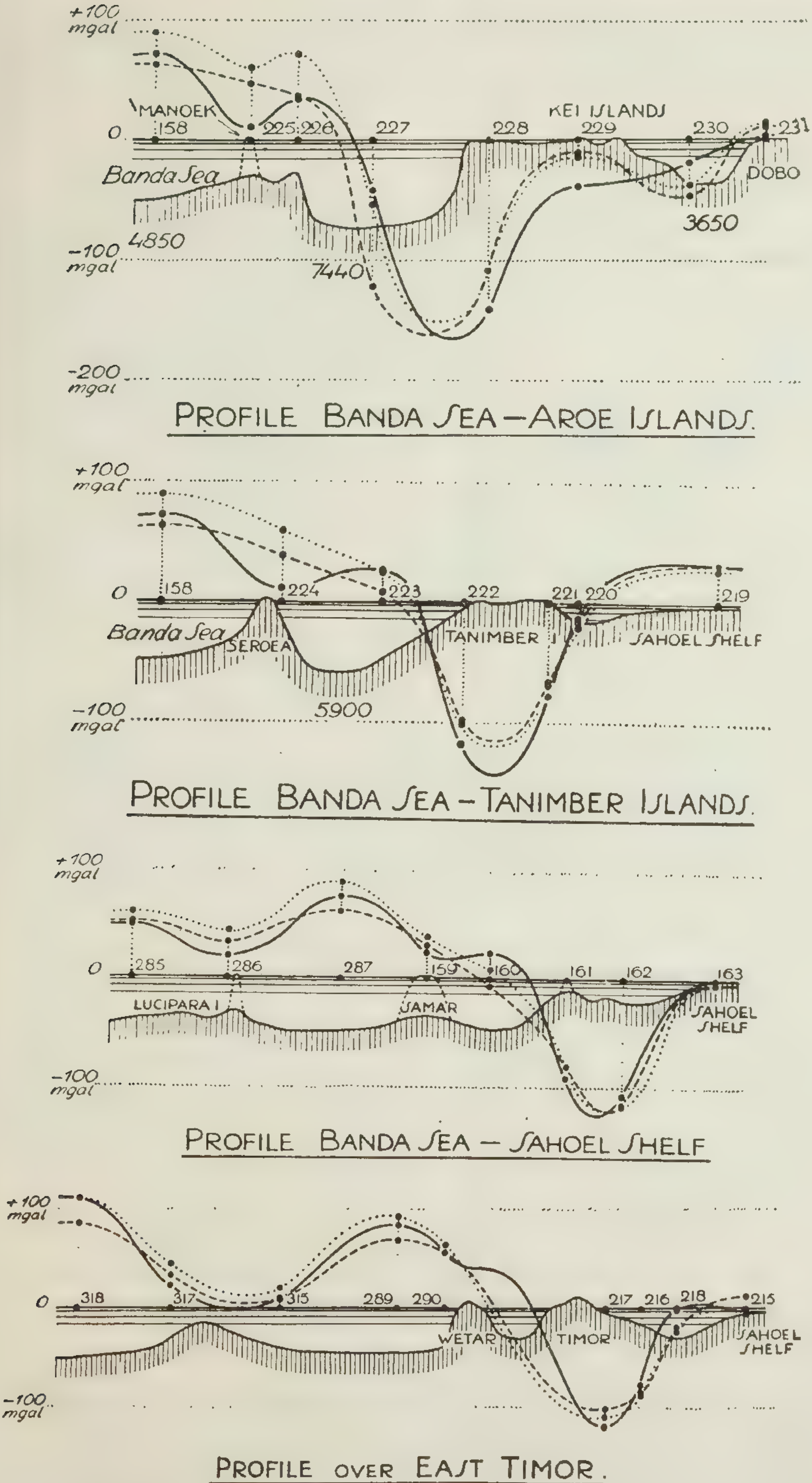
The gravity profile over the edge of the Sahul Shelf is very similar to that found in Vening-Meinesz (1941) over other continental shelves, although the other shelves are opposite ordinary ocean depressions, while the Sahul Shelf is opposite a mobile island arc in active process of deformation.

(b) *Seismicity.*

From the evidence of the coral reef studies (Teichert and Fairbridge, 1948), of the asymmetric section of the Timor Trough, and of the gravity anomalies, it would appear that the trough between Australia and the East Indies is now subsiding, or up till recently has been so.

Possibly in part because there are no recording stations, seismic data are rather sparse along this trough, as compared for example with those from the Java Trough, but a moderate number of records exist. On the 16th August, 1929, a medium-heavy earthquake was identified with an epicentre about $16\frac{1}{2}$°S., 121°E. (Gutenberg and Richter, 1949). The degree of error is plotting its position is unfortunately rather large (3°), but it probably lies somewhat south-west of Scott Reef.

Futher indications occur all along the trough ; it appears that a heavy shock occurred at 8°S., 132°E. (130 km. S.E. of Tanimbar), while four slight shocks occurred in the Roti-Timor-Sermata section, and numerous ones in the Aroe-Bomberai section. Since the interior of the Banda Arc is one of the



Text Fig. 6.—Gravity anomalies near the edge of the Sahul Shelf.
(From Vening-Meinesz, 1934.)

N.B.—Dotted line indicates the Hayford-Bowie anomalies; broken line the Heiskanen anomalies; solid line the Regional anomalies.

most highly seismic zones of the East Indies, it is, however, not altogether surprising that minor shocks occur between its margin and the stable continental borders. The problem of deep-focus shocks and the idea of the rising shear zone under such island arcs have recently been widely discussed.

(c) *Topographic and Geological Data.*

In discussing the intercontinental relationships of Australia and Asia, in particular in the narrow belt between the Sahul and Arafura Shelves and the Sunda arcs of the East Indies, probably the most important point is the apparently uniform continental nature of the whole mass of North Australia with its continental shelves, Aroe and the southern parts of New Guinea. A spur of this continental mass extends into the eastern Mollucas to Misool and Soela (the "Soela Spur" of Stille, 1945), though Glaessner (1950) has suggested that the parallelism of the Vogelkop folds with the Banda Arc indicates some mutual relationships. A deep (1,000 fathom) trough separates the Australia-Misool block from the rest of the Moluccas.

In certain respects the stratigraphy of the Moluccas has similarities with that of the adjacent Australian block. Mutual relationships in shallow-water faunas extend between N.W. Australia, Timor, New Guinea and the Moluccas right back to late Palaeozoic times (Wanner, 1931 ; Teichert, 1941, etc.). The periodic transgressions of epi-continental seas over this region would imply a continental foundation. Such facies could not be correlated with deep sea environments.

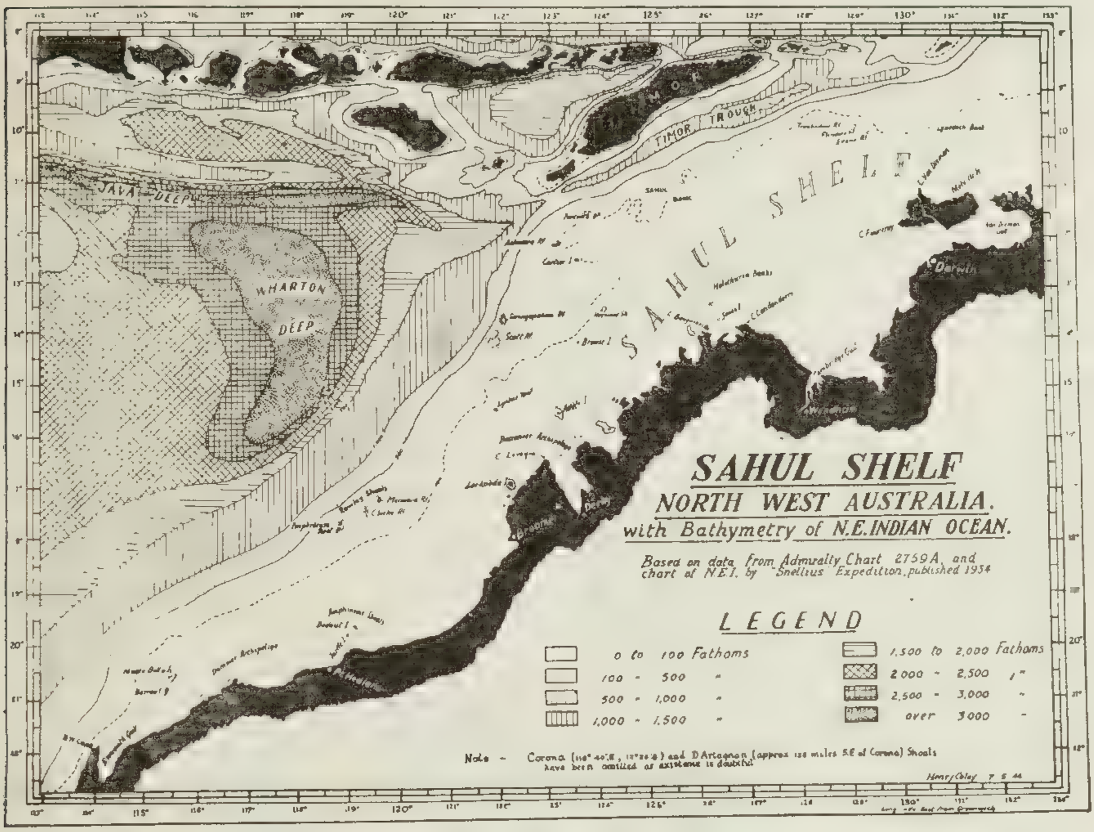
Little is known of pre-Permian rocks in the eastern parts of the archipelago. Both Devonian and Silurian are found in New Guinea (Umbgrove, 1938). Rocks older than the Permian, wherever exposed in the area from Timor to Celebes, are intensely metamorphosed and must have been folded during a pre-Permian orogenic cycle, which in turn must have been separated from the Permian sedimentary cycle by a long period of emergence. Again, the implication is that continental conditions must have existed here even in fairly remote times.

During Permian and Trias, a geosynclinal environment became impressed on the Timor-Ceram arc, as indicated by the characteristic facies, with flysch, ophiolites and so on (Umbgrove, 1938). This mobile belt later became affected by intense orogenic disturbances with nappe structures. On the other hand, in the northern Moluccas the Mesozoic rocks still exhibit foreland characteristics, resting more or less horizontally in gently tilted fault blocks (Wanner, 1931).

The principle orogenic phase in the collapse of the Outer Banda Geosyncline (Timor-Ceram arc) was Miocene with some movements continuing till today. Probably more or less coincident with this phase has been the fragmentation and foundering of the present deep basins in the eastern archipelago (Kuenen, 1935). As Kuenen has repeatedly emphasised, this present topography appears to be an essentially youthful feature.

Palaeogeographically there seems to be evidence for repeated land connections across the Moluccan region, reaching back into the Palaeozoic. Abandanon (1919) imagined a Palaeozoic continent "Aequinoctia," which was to have stretched from Tasmania to Celebes. Its break-up began, he believed, in Carboniferous times, though it is only in Permian and Trias times

that we encounter geosynclinal facies. The extension of the Banda Geosyncline during the Trias to continue these conditions round northern New Guinea to New Caledonia and New Zealand (Benson, 1923, 1924, 1925) is particularly interesting. This belt would appear to be cutting the old "continent" completely in two.



Text Fig. 7.—Sahul Shelf, with bathymetry of N.E. Indian Ocean.

A "Sino-Australian Continent," postulated for Jurassic times by Neumayr (1883), is thus improbable, though Arldt (1938, p. 33-6) accepted it on zoogeographic grounds, considering it an essential route for the early monotremes (*e.g.*, ancestors of Echidna and Platypus), migrating to Australia. Umbgrove (1935) also considered the probability of a late Mesozoic land-bridge here, though perhaps only as island "stepping-stones" in places, for the floral differences alone between the Mesozoic of Cathaysia and Eastern Australia do not appear to favour a continuous connection. In the early Eocene times a continental connection at least between the Moluccas and Northern Australia was considered probable by Höfer (1908), and with further evidence is reviewed by Kuenen (1935). For later times, Mayr's results are particularly interesting (*see* Sect. IId.).

From the topographic point of view, Kuenen (1935) has demonstrated that it is difficult to draw a hard and fast line between Australia and the East Indies, especially in the New Guinea-Halmahera region. The Timor Trough does not seem to possess the characteristics of an ancient structural "seam." Earlier interpretations conceive the Banda arcs as a row of horsts, separated from Australia by a graben zone (Suess, in Sollas translation, 1908, vol. 3, p. 237; also Martin, 1890; Gregory, 1923). A new conception resulted from Molengraaff's discoveries of low-angle overthrusts in Timor (1913), and Brouwer (1920, 1925) also developed the idea of an overthrusting of the Outer Banda

arcs onto the Australian block, which was to represent the traditional "foreland." The corollary of an underthrusting *vice versa* followed almost automatically. The sharpest curve of the arc through Kei and Tanimbar Islands appeared to be conditioned by a pre-existing "gulf" in the northern Australian continental block.

The extreme development of the horizontal displacement concept was the idea that Australia impinged on the East Indian arcs as late as Tertiary times, the continental drift theory of Wegener (1924), found its complete contrast in the "undatory" theories (with vertical movements primarily) of Stille (1920) and van Bemmelen (1933, 1950).

The *Snellius* Expedition provided more data on the present morphology of the basins and islands of the Moluccas, and Kuenen concluded that if there had been any major drifting, then it must date from a time well before the development of the present relief (1935, p. 105). As regards the Timor-Aroe Trough, Kuenen has demonstrated a roughly synclinal morphology in contrast to the *en bloc* subsidence or rift-like characters of most of the other Moluccan deeps.

This might favour the idea of horizontal movement, but geomorphological evidence recently confirmed by air photographs suggest that vertical movements are now going on. This was the conclusion of Molengraaff (1913), who found the south coast of Timor normally down-faulted, and the sonic sounding of the *Snellius* Expedition has demonstrated what appear to be great normal faults in the floor of the Timor Trough (*see* text fig. 8). It seems that the trough subsided in late Tertiary/Quaternary times, along with the vertical elevation of Timor (Pleistocene coral reefs stand at over 4,000 feet), while in the south the margin of the Sahul Shelf has been tilted down.

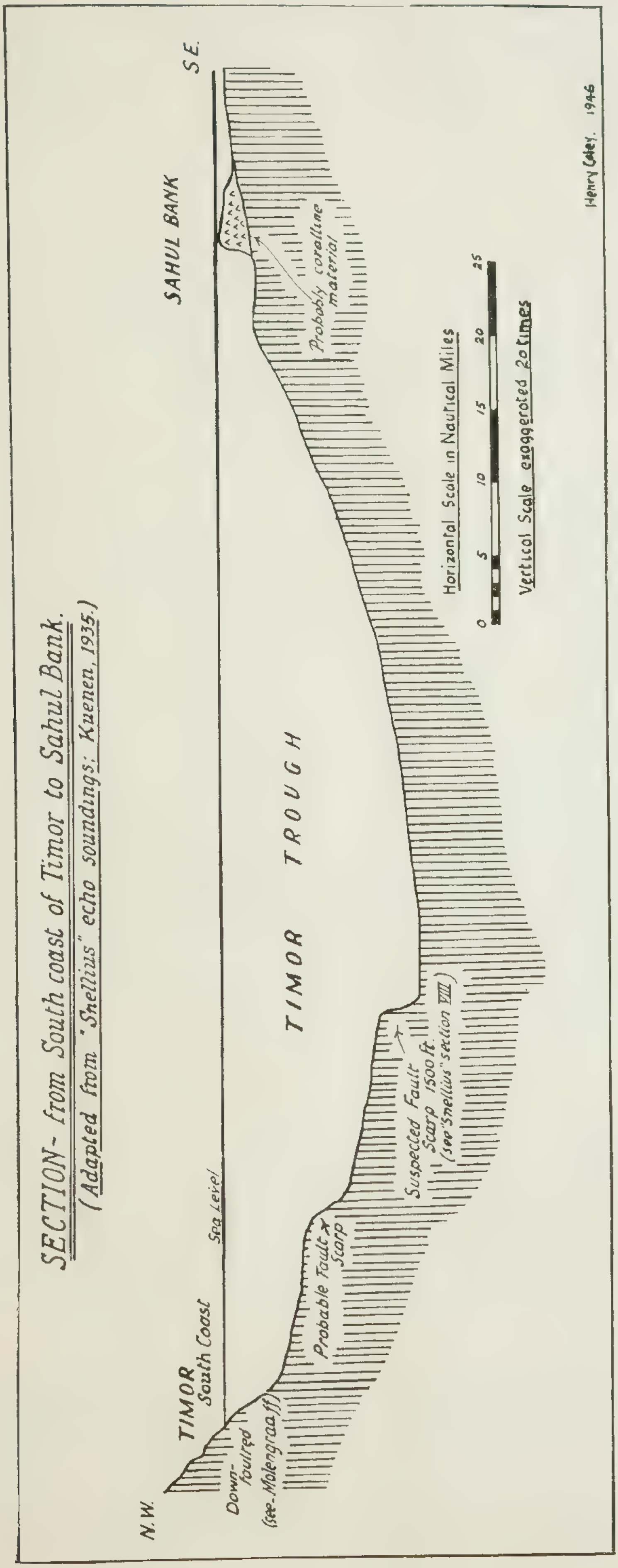
On the evidence of geophysical material, Vening-Meinesz (1934) concluded that the Banda Arcs are now being involved in a gigantic down-fold (kink) of the earth's crust, a concept which seems to accord with the structural demands (Umbgrove, 1947a). A degree of asymmetry and horizontal movement is recognised in this kinking, which corresponds to the known topographic features and to the rising shear deduced from deep-focus earthquakes.

There seems thus to be evidence for concluding that the present geomorphologic relationship of the Outer Banda Arc to the Timor-Aroe Troughs and the Sahul-Arafura Shelves is a relatively recent (*i.e.*, late Tertiary and Quaternary) phenomenon. The relationships between the Mesozoic-Tertiary mobile zone and the semi-rigid foreland appear to follow out a normal transition in the northern Moluccas, though are obscured in the Timor Trough-Sahul Shelf sector. In the Banda Arcs there is no sign of the borders of the ancient Australian continent, which may have extended much farther north and west than it does today.

VI. DISCUSSION.

In its position between Australia and Asia, facing the East Indian Archipelago, the Sahul Shelf occupies a critical zone. Matters of fundamental importance to Australian-Asiatic geotectonics and palaeogeography are bound up in this region.

The alternating rises and depressions of the Sahul Shelf seem to be situated opposite plateaus and basins on the land, and thus stand in genetic relationship to the structure of the mainland. Just as the plateaus are correlated with a more or less rigid basement of older Pre-Cambrian, sometimes



Text Fig. 8.—Section from south coast of Timor to Sahul Bank.

overlain by a thin veneer of younger sediments, the rises of the Sahul Shelf appear to have a similar Pre-Cambrian basement, though locally obscured by a thin film of younger material. Slow sedimentation only is now in progress on the shelf and the thin sedimentary veneer over the granite core in the Aroe Islands is very significant, as these islands are situated on one of the shelf rises.

In the shelf depressions on the other hand, one will expect a thicker accumulation of sediments, and all the formations recorded from the adjacent mainland basins should be found here too. As already noted, Wade (1924) and Clarke (1938) have mentioned the analogy between the "Palaeozoic Sunkland" of the Desert Basin and the two great gulfs further east, our Bonaparte Depression, and the Gulf of Carpentaria. These giant embayments are, in fact, but little different from one another, except that the two gulfs are "drowned" by relatively shallow expanses of water, while the Desert Basin is only slightly higher. All were probably gulfs periodically through the Palaeozoic, and they were repeatedly invaded at various times in the Jurassic, Cretaceous, Tertiary and Quaternary.

All the shallow shelf depressions are thus probably marginal basins of sedimentation in condition of growth today, undergoing slow local subsidence. They may, in fact, be regarded as contemporary "paralic basins" of sedimentation (Tercier, 1939), or "discordant basins" (Umbgrove, 1947a), of the types identified already in north-west Australia of late Palaeozoic origin (Teichert, 1947).

The quantitative question of how much relative elevation and depression has occurred between the blocks is of some consequence. Wade (1924) has remarked on the thinness of the post-Nullagine sedimentary cover on the rising blocks (of the order of under 500 feet). For depressed blocks, such as the Desert Basin and East Kimberley, Teichert (1947) has given a maximum of 3,000 feet for the Cambrian (not counting the basalt flows), 10,000 feet for the Devonian and 10,000 feet for the Permian. Evidence from bores near Broome and Derby suggest a post-Permian (Mesozoic to Recent) accumulation of about 2,000 feet. The total amount of sedimentation comes thus to 20 to 25,000 feet, but it may not have occurred all in one place, rather in different parts of the depression, locally being removed by erosion, so that the floor of the basin would possibly not exceed a depth of 10,000 feet today. If it were much deeper one would rather expect to find some major folding, which is notably absent (Fairbridge, 1950a).

The bulk of the movement in the mainland basins was completed by the end of the Palaeozoic and, save for some revival in Tertiary, a relatively high degree of stability has continued thus during very long geological periods. Marginally, in the shelf depressions subsidence is still in progress. Over the rises we may possibly expect only a thin layer of post-Archaean sediments, possibly hardly any at all, while in the depressions, by analogy of course with the great basins of the mainland, we may expect up to 25,000 feet of sediments. Again, it is doubtful if this column would be found all in one vertical section.

These discussions have some bearing on contemporary ideas of continental shelves in general, which have greatly developed during the last decade or so. Roughly, there are three theories as to the structure of continental shelves :

(a) They generally consist of ordinary continental rocks *in situ* planed down by erosion (von Richthofen, 1886 ; Buchanan, 1887) ;

(b) they consist of a giant lens or wedge (the "Transitional Area") of young continental sediments, distributed out to wave-base (Murray, 1885);

(c) they consist of a combination of the two, a broad notch cut in the continental rock, with an apron of sedimentary debris spread out in front (Fenneman, 1902; Johnson, 1919; and Daly, 1927).

Without making a detailed analysis (see, for example, Cotton, 1918; Umbgrove, 1947a; Shepard, 1948; Kuenen, 1950), it can be seen that each has its virtues, though the last seems most logical, and certainly seems to be true for the North Atlantic continental shelves according to geophysical evidence, both on the American side (Ewing *et al.*, 1937) and on the European side (Bullard and Gaskell, 1941).

In the northern Australian region, however, it rather looks as if all three structural varieties occur. A section run from Torres Straits to Aroe would show a shelf with crystalline basement, almost horizontal, with but the thinnest veneer of recent sediment on it (type "a"). Opposite the Desert Basin, in the Rowley Depression, probably a very thick wedge of sediments extends from far inland to several hundred miles off-shore (type "b"). The Browse Depression is clearly of the combination sort (type "c"), where the inner 50 100 miles is marked by continental islands, grading out to what appears to be a smooth-surfaced sedimentary lens beyond.

The explanation of the actual erosive sculpturing of the shelf is a further problem, which also resolves itself into three choices:

(a) Mechanical erosion by waves operating to wave-base (von Richthofen-Fenneman-Johnson school).

(b) Subaerial and shore-line erosion under conditions of shelf-emergence, due to:

  (i) Glacio-eustatic lowered sea-levels, or

  (ii) Tectonically flexed continental margins.

The present writer has tried to show that shore-line or inter-tidal erosion (where waves remove the mechanical debris, already dissolved and loosened by subaerial erosion) is so much more important on rocky coasts that Fenneman's and Johnson's smooth "profile of equilibrium" will never be achieved (Fairbridge, in press). Shore-line erosion during Pleistocene low eustatic oscillations provides for a limited amount of planation down to 50–60 fathoms (Umbgrove, 1929; Zeuner, 1945), where coarse littoral sediments of apparently Pleistocene origin are found (Fairbridge, 1946).

The low outer edge of the Sahul Shelf (300 fathoms) certainly favours the marginal flexure idea (Bourcart, 1938; Jessen, 1943), but it is so exceptionally low that there may be an unusual condition operating here today; its juxtaposition with the subsiding outer trough of the East Indian mobile belt is suggestive. The evidence of large atolls and the traces of an imperfect barrier reef along this border is indicative of subsidence (Teichert and Fairbridge, 1948).

VII. CONCLUSIONS.

Summarising our conclusions, therefore, we find that :—

1. The Northern Australian continental shelves are divisible conveniently into three ; The Rowley Shelf (west of Cape Leveque), the Sahul Shelf (*sensu stricto*), and the Arafura Shelf (east of Cape van Diemen, but not including the Gulf of Carpentaria, which is contiguous to it).
2. The topography of the Sahul Shelf demonstrates evidence of subaerial exposure and erosion, including :
   (a) Plateau, terrace and cuesta type of topography.
   (b) Shallow submarine canyons crossing the shelf.
   (c) Traces of grain of older rocks in submerged ridges.
   (d) Pleistocene migratory routes shown by zoogeographic material.
3. The edge of the Sahul Shelf, at about 300 fathoms, is abnormally low, and may be explained by a slow subsidence, tilting down the continental margin opposite the East Indian arcs (an explanation favoured by the occurrences of coral atolls and interrupted barrier reef here).
4. A major " step " or break in the slope of this shelf is recognised in many places at about 55 to 60 fathoms, which may mark the break between two major cycles of subaerial erosion of the shelf, the lowest Pleistocene sea-level being generally taken as 55 fathoms.
5. Structurally the Sahul Shelf also exhibits transverse divisions into slightly higher and lower areas, termed here " rises " (10 to 40 fathoms) and " depressions " (40 to 70 fathoms).
6. The adjacent continent is found to consist of even more marked swells and basins, which exist not only topographically, but also structurally and stratigraphically.
7. The swells on the continent are major tectonic blocks of older pre-Cambrian age, peneplaned and overlain by thin deposits of subsequent periods. Their structural attitude is horizontal or undulating except near the faulted and flexed margins.
8. The basins on the continent are of considerable geological age. Downwarping occurred in them periodically from Cambrian to Recent. Thick deposits of sediments have accumulated in them (up to 25,000 feet, but probably not all in one place).
9. Depressions and rises of the shelf are arranged opposite the basins and swells of the continent. Their structural histories appear to be analogous.

Thus we recognise from west to east :

On the continent.	*On the shelf.*
Pilbara Block	Dampier Rise
Desert or Canning Basin	Rowley Depression
Leopold Range	Leveque Rise
No equivalent	Browse Depression
North Kimberley Block	Londonderry Rise
East Kimberley Basins	Bonaparte Depression
Pine Creek-Darwin Ridge	Van Diemen Rise
N.E. Arnhem Land—Wessel I. Ridge	Wessel Rise

Beyond the Van Diemen Rise we are already on the Arafura Shelf, with an Arafura Depression (Fairbridge, 1951) corresponding to the Torres Straits depression between New Guinea and Cape York Peninsula; the Merauke Rise, corresponding to the Oriomo uplift of southern New Guinea; and, finally, the Snow Mountains Trough, in direct continuation of the Papuan Trough farther east. East of the Arnhem Land block lies the Carpentaria Depression.

10. Continental rocks on the Sahul Shelf are unknown except quite close to land. On the Arafura Shelf, however, the Aroe Islands provide a valuable "window," serving to show the underlying rocks: apart from Tertiary shallow-water marine sediments, there is a small occurrence of granite, indicating the continental basement at shallow depth, as also in southern New Guinea.

11. The only other islands on the shelf are coral islands. These springing from shallow water may have grown up from the bottom; those from moderate depths may be traced to the fringing reefs of Pleistocene low eustatic sea levels. But those rising from 100 to 300 fathoms require some element of subsidence to explain them. These deep-seated reefs (mainly atolls) rise from the areas already regarded as subsiding depressions on other grounds.

12. Contemporary sedimentation on the shelf areas is not well known, but wherever sampled suggests either local sedimentation due to coral reef erosion, or elsewhere show terrigenous sedimentation with glauconite muds and residual sands. Here sedimentation may even be suspended for long periods and more resistant minerals are concentrated by reworking. A thin veneer of younger sediments is thus to be expected over the rises, and even in the depressions, where representatives of most geological periods may be predicted, many are likely to be in reduced sequences because of the regional history of low relief and slow sedimentation.

13. Stratigraphic and palaeogeographic data indicate that much of Northern Australia and its continental shelf region have been continental since Archaean times; all subsequent sediments are neritic in character with no trace of deep-sea or ortho-geosynclinal facies. Sedimentary basins in the area cannot therefore be considered as as ortho- or para-geosynclines, and are perhaps best described as *paralic basins* (Tercier).

14. Palaeogeographic and faunistic connections suggest that this continental area (either as land or shelf) formerly extended far to the north-west, including the northern Moluccas in Mesozoic times and possibly even to reaching to the Celebes in the late Palaeozoic. The geosynclinal evolution of the Timor-Banda Arc set in with the Permian and Trias, apparently encroaching on the old continent.

15. The unmodified (original) Wegenerian idea of an Australian continent, drifting several thousand kilometers to impinge upon the Moluccan region in late Mesozoic to Tertiary times, cannot therefore be entertained.

16. From Timor south-westwards, however, there is nothing to suggest that the present limit of the continental shelf (and slope) has not approximated to the margin of the continent for very long periods.

17. Palaeozoic land connections between Australia and the rest of Gondwanaland could not have been towards the north-west, because repeated marine invasions seem to have come from this direction. In Permian times continuous marine connections reach down from the Moluccas as far as 30°S. latitude, so that any land connection with the rest of the Gondwana units would have to be via the extreme northern or southern parts of the continent, not the west. Alternatively, the biogeographical data might perhaps be explained by island links.

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2.—BEACH SAND MOVEMENTS AT COTTESLOE, WESTERN AUSTRALIA.

By

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CONTENTS.

ABSTRACT.

Investigation into the serious erosion of the beach at Cottesloe lead to more wide-spread investigation into the general movement of sand in the area known as Cockburn Sound and Approaches to Fremantle. The movement of sand throughout the area and the mechanics of the sand movements at Cottesloe are discussed in relation to the various conditions of weather, currents and wave actions.

I. INTRODUCTION.

Cottesloe is situated at 31° 59′ S., by 115° 45′ E., on the west coast of Australia, about 3 miles north of Fremantle Harbour and approximately 8 miles from Perth. From the year 1900 to about 1940 Cottesloe was a fashionable bathing beach and summer resort, but owing to increasing beach erosion that has become especially apparent since 1940, the popularity of the beach has declined, so that by 1950 the bathing pavilion and other amenities built in 1929 were no longer showing a profit.

In 1906 a jetty had been built after the style of the piers of the south of England, having band stands, etc., along its length. The beach then was quite extensive. The next major " improvement " was in 1929, when a large bathing pavilion with shops and other amenities was erected. A retaining wall and promenade were built along the front of the buildings, thereby encroaching slightly on the beach. Also, a large parking area was built on the dunes just north of the pavilion. At this time (1929) there was still ample sand to form a good beach.

About 10 years after the pavilion was built it became apparent that the sand was getting thinner, as during heavy winds and storms the rock below the beach was being uncovered. This condition has steadily deteriorated until now the beach is often unusable because of jagged underlying rock being stripped bare of sand for the greater part of the summer. The jetty is still in existence, but, owing to damage by storms and lack of maintenance, is less than one quarter its original length.

In 1949 the Cottesloe Council, through its Councillor Mr. F. G. Forman, former Government Geologist, and Dr. R. W. Fairbridge, of the University of Western Australia, agreed to help defray the expense of beach erosion investigation, which led to the writer undertaking one year's research on this problem as part of his fourth year of study in geology at the University of Western Australia under the direction of Dr. Fairbridge. The Council met the cost of the air photos taken by Airsurveys Pty., Ltd., during the year, and also defrayed the incidental expenses arising during the investigation.

The method of work was, firstly, an extensive reading of the literature available, together with frequent visits to the beach. From preliminary observations and the information gained from the literature, it was apparent that some type of standard observation sheet would be necessary. Thus an outline table of observations to be made on each visit was drawn up and used throughout the investigation. The original table was amended later in the year to give a more complete coverage of the variable factors.

From the outset it was realised that a continuous record of the weather conditions would be necessary, so the daily weather bulletins were obtained from the Divisional Meteorologist, Perth, and these were invaluable, especially when used in conjunction with the air photos.

During the year, six vertical line-overlap aerial photograph runs were flown ; run 1 taking in the beach from 3 miles south of Cottesloe to a point approximately 10 miles north of Cottesloe ; runs 2–6 being only repeat coverage of selected portions of run 1. Some selected obliques were taken at specific times, but there was no attempt to give any sort of general coverage by obliques. These photographs are kept in the Geology Department of the University of Western Australia.

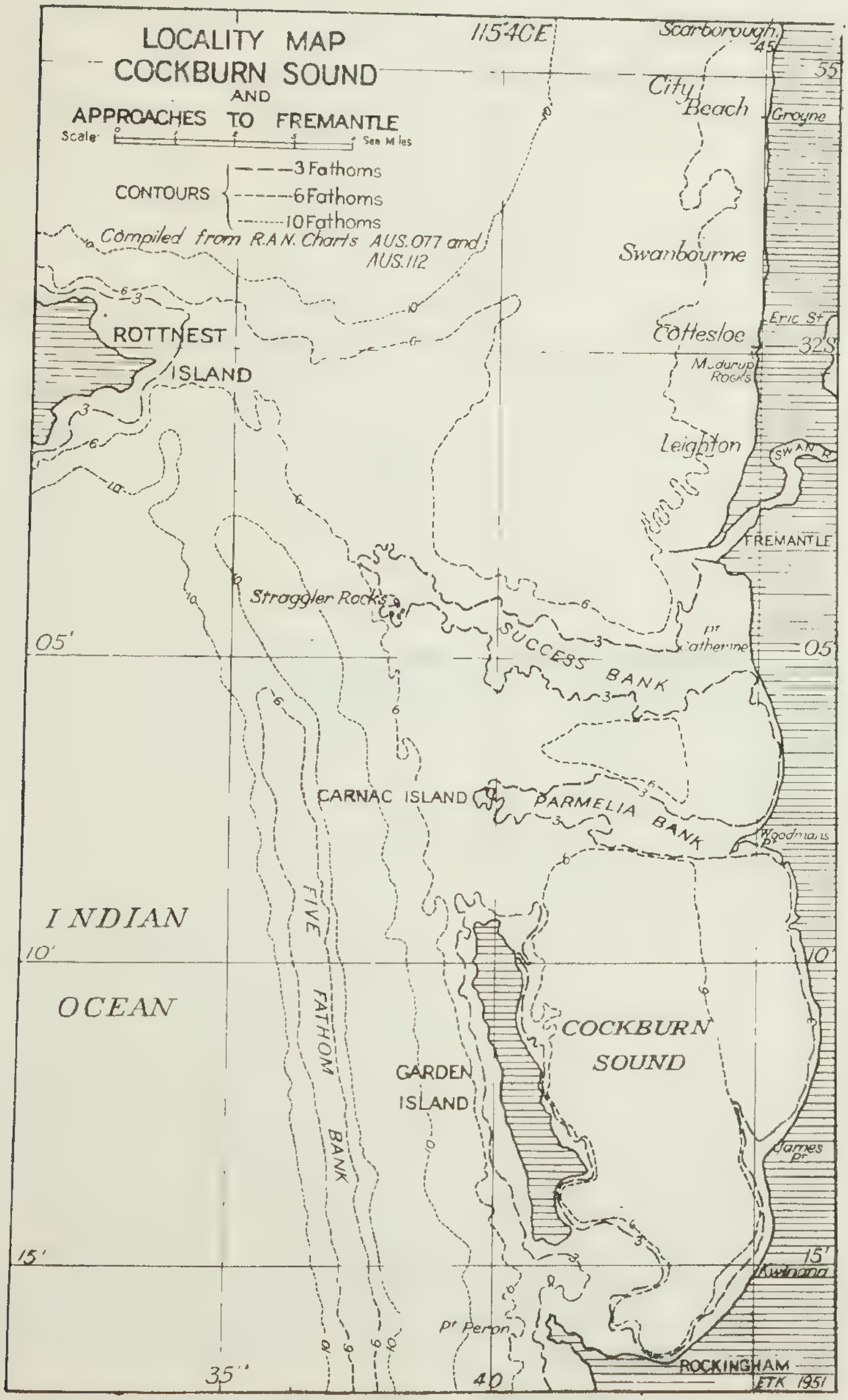
Details of the above aerial photographs, together with the tides for the preceding 48 hours and the winds for the previous four days, are given in Appendix I.

Some attempt was made to study the problem of beach erosion using sedimentary petrographic methods, following the methods and conclusions of Krumbein (1941) and Rittenhouse (1943a, b), but owing to many factors beyond control and the fact that all the sand originated from the same distributive province, namely the Pre-Cambrian of the West Australian Shield, it was realised that little result could be expected, and consequently the time was devoted to other avenues of approach.

Finally, the writer would like to express his wholehearted thanks to the Cottesloe Council for making this investigation possible, to Dr. R. W. Fairbridge, whose guidance and advice has been of very great assistance, and to Mr. N. J. Henry of the Harbours and Rivers Branch of the Department of Public Works, for his co-operation and information.

II. GENERAL DESCRIPTION OF THE AREA.

Before dealing with Cottesloe in particular, general consideration is needed of the unit area, which may be taken as Cockburn Sound and the approaches to Fremantle (*see* Locality Map, text fig. 1).



Text fig. 1.

General locality map showing Cockburn Sound and the approaches to Fremantle.

A comparison of the old maps of Archdeacon and Coghlan, prepared in 1874 with the 1947 R.A.N. charts, shows that, in general, only minor variations have occurred in the distribution of offshore sediments. The two sand banks in Cockburn Sound, namely Parmelia and Success Banks, have not changed to any noticeable extent.

Coastal Features.—In a paper on Point Peron, Fairbridge (1950) described the types of coastal features that are common throughout the area. Many similar geomorphological features are also found at Rottnest Island (Teichert, 1950) and at the Abrolhos Islands (Teichert, 1947 (b), Fairbridge, 1948). Along much of the coastline and, in particular, from Fremantle to Swanbourne, there is a considerable outcrop of the sandy limestone known in Western Australia as the Coastal Limestone Formation (*see* Teichert, 1947 (a)). Low cliffs of this rock have been benched at various levels corresponding to the 3 ft., 5 ft. and, in places, to the 10 ft. eustatic sea-levels described by both Fairbridge and Teichert.

Mudurup Rocks at Cottesloe show the remnants of a 10 ft. platform and, to a lesser extent, evidences of a 5 ft. bench. There is a well-formed contemporary bench at Mudurup Rocks. Just south of Mudurup, *i.e.*, at the foot of Jarrad Street, there is a well-preserved 5 ft. bench, whilst from 100 yards south of that bench to 200 yards north of Leighton, there is an almost continuous 3 ft. bench. Some two miles south of Cottesloe two " fossil stacks " were found, remnants of the 5 ft. sea-level, and a well-marked 10 ft. bench.

An old drawing in the Public Library, Perth, dated 1832, shows the site of Fremantle to be on a tombolo, *i.e.*, a rocky island tied by a sand bar to the mainland. The head of this tombolo was Point Arthur. Behind the South-east Beach was a lagoon running parallel to the shore. This lagoon was just south-east of the position of the Round House.

Another such lagoon existed at South Beach. Until reclamation work was carried out by the Fremantle Council, South Beach was an offshore bar with a lagoon where the railway now runs. This lagoon was connected with the sea by a shallow opening in the bar, over which fishermen used to take their boats for shelter during bad weather.

It is probable that the Swan River once flowed out into the sea through this area, *i.e.*, to the south of Point Arthur. This is suggested by the discoveries of evidence of old shore lines in wells in this area. Shallow holes put down at the back of South Beach about a quarter of a mile from the sea, also show bands of fine mud which is very much like the river mud of today. This suggests that the area south of Fremantle was once a river flat. The river was forced to the north by a cumulative movement of sand from the south, and took up a position between Point Rous and Point Arthur.

To the south of Fremantle is Cockburn Sound. This sound is almost landlocked on three sides, namely east, south and west, and to the north is practically sealed by Parmelia and Success Banks.

These two banks trend roughly at right angles to the coastline (*see* text fig. 1). They are not controlled by a rock bar structure, *i.e.*, they do not have a core of rock, but as far as is known are composed entirely of sand. During the dredging of channels through these banks nothing but sand was encountered. The depth of water in the Sound is down to 10 fathoms (60 feet), while the banks rise abruptly to less than 10 feet of water and are almost awash in places. The bottom of Cockburn Sound is a grey calcareous ooze.

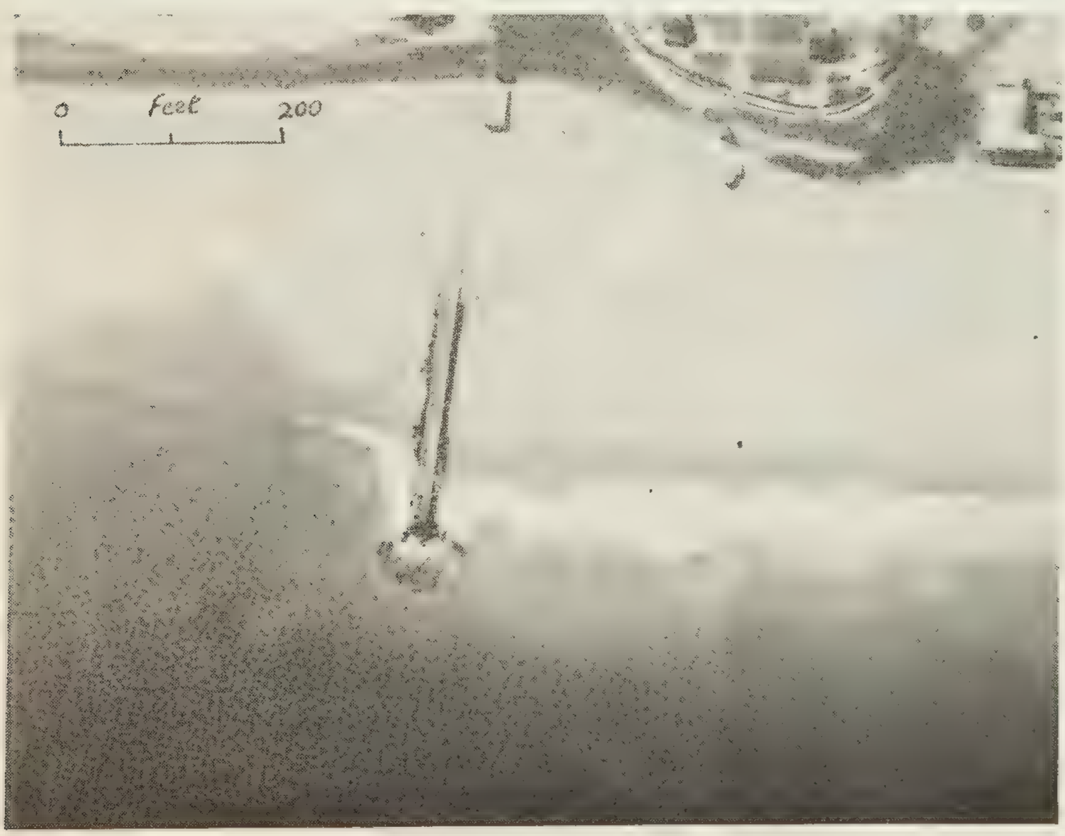
Analyses of sand from the banks show about 95 per cent. carbonate (from N. J. Henry, Public Works Department, personal communication), suggesting either that it is of littoral drift origin, *i.e.*, composed of light current-born

material, or that the banks are the site of former shell colonies that are now extinct. These sands are extremely fine so that the second hypothesis is unlikely. Because of their high carbonate content, it is most probable that the banks are composed of sand derived from broken shells and transported by littoral drift from beaches farther along the coast. Grant and Shepard (1940) found that similar banks built up in deep water in Santa Monica Bay, California, were composed of fine sand of high carbonate content, and mostly finer than 0.125 mm. diameter.

Woodman's Point and Catherine Point were probably both formed by building up of sand on the eastern end of the banks by wave and wind action.

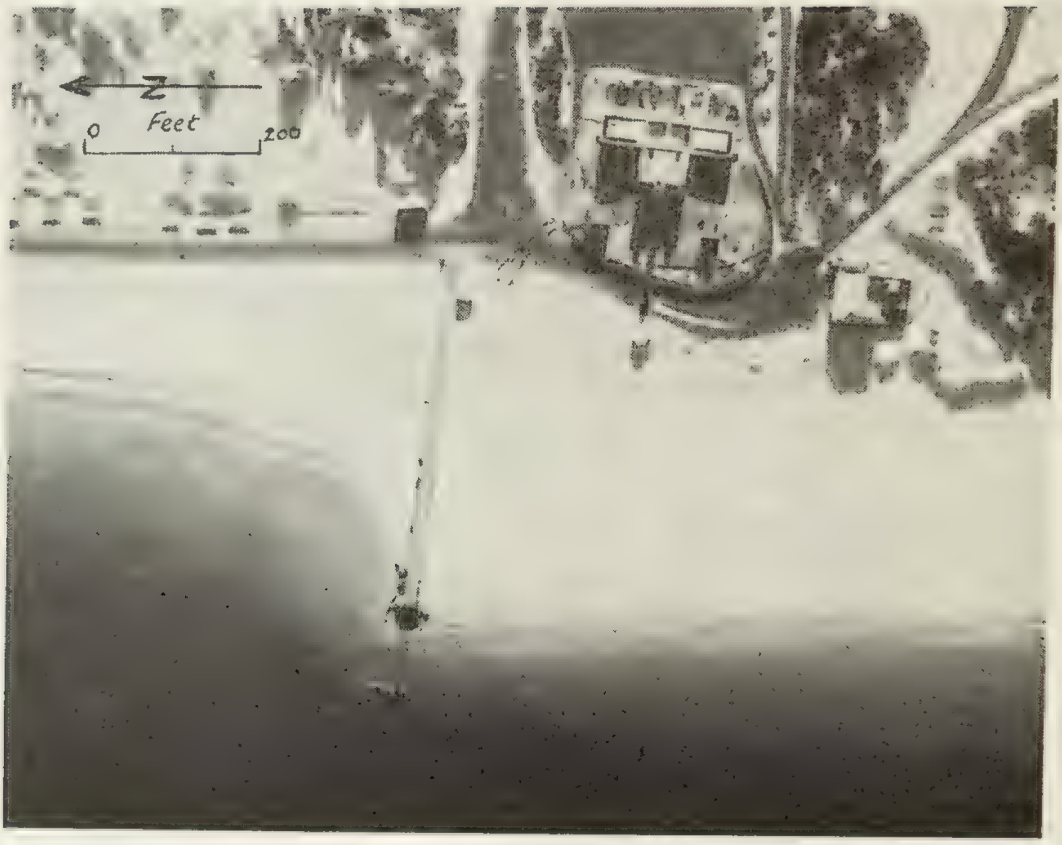
Engineering Works.—When Fremantle Harbour was constructed in 1890, two moles were built out to sea roughly at right angles to the general direction of the coast. North Mole is approximately 5,000 feet long, whereas South Mole is only about 2,500 feet. The landward bases of the moles were the two rocky heads of the river mouth, Point Rous on the north and Point Arthur on the south.

A short masonry mole or groyne was built about 15 years ago at City Beach, some 6 miles north of Cottesloe. This groyne is 400 feet long and was built for beach protection, and from the result observed was a complete success, a broad beach always forming on one side or the other according to the season.



Text fig. 2.

Winter conditions at the City Beach groyne are shown in this vertical of the beach. (North is to the left of the groyne looking from the sea.) A comparison with Text Fig. 3 shows the marked difference between summer and winter conditions.



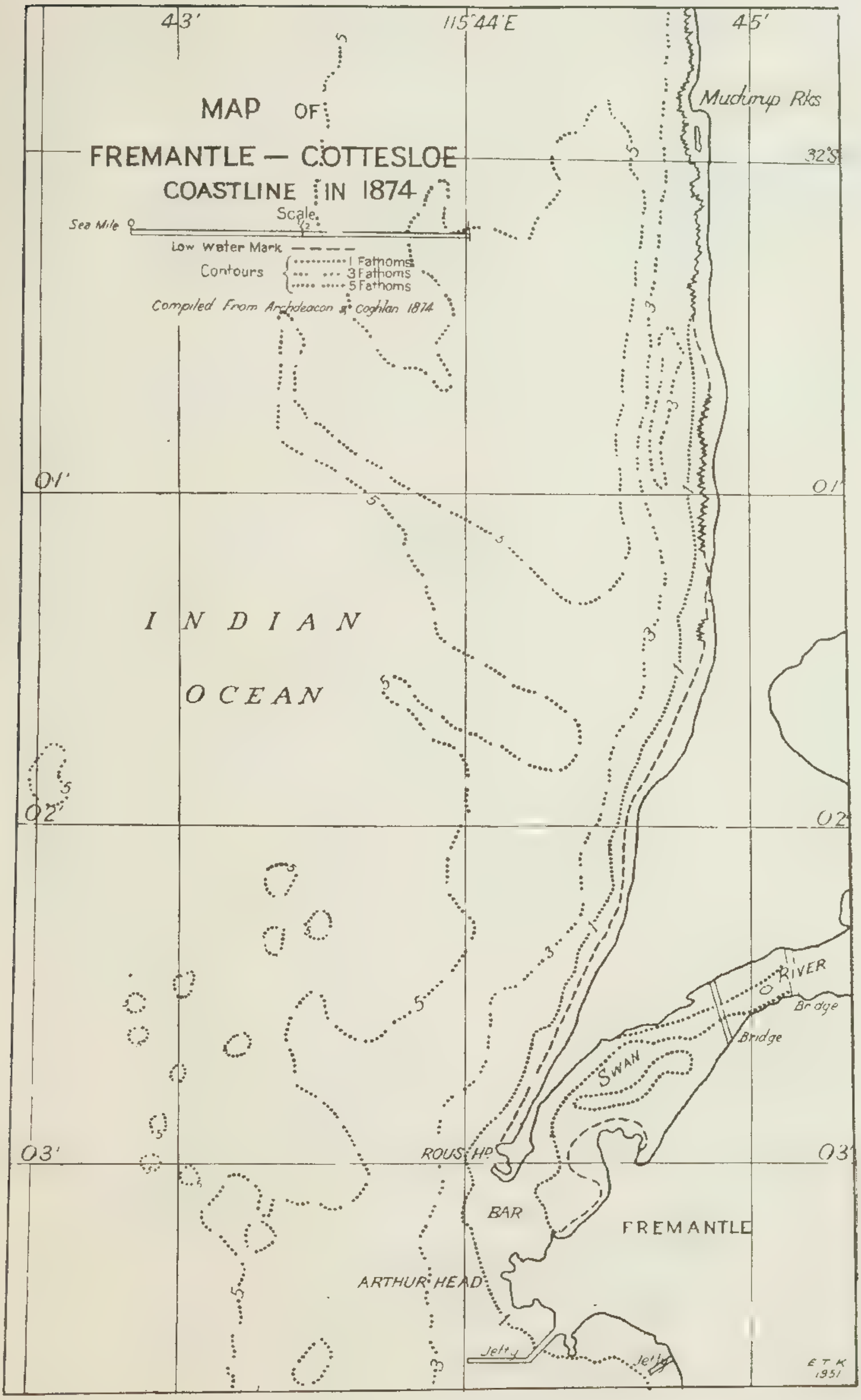
Text fig. 3.

Portion of a vertical aerial photograph showing the groyne at City Beach as it appears under summer conditions of maximum sand accumulation on the south side of the groyne. (Compare with Text Fig. 2 showing winter conditions). The aerial photograph was taken on 14th February, 1949.

Two groynes and a short section of sea wall were built between 1946 and 1949 in connection with the new South Fremantle electric power station. Time has not yet permitted adequate appraisal of their effect.

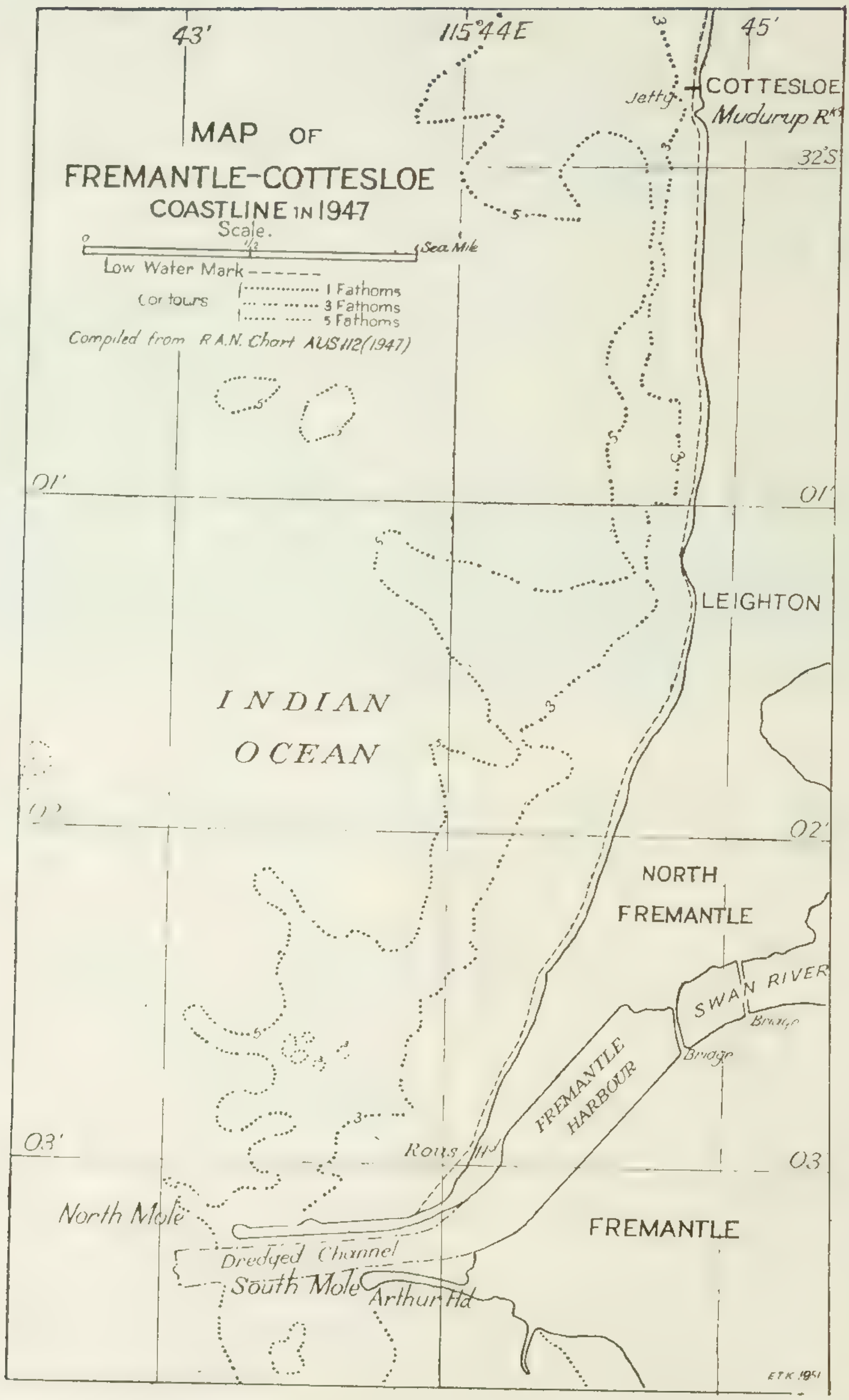
All the abovementioned groynes and the wall were of masonry. Some timber groynes were built at South Beach, Fremantle, but, together with the sea wall behind them, they have been washed away in storms. An experimental wooden groyne (56 feet long) was put in near the base of Cottesloe Jetty, but it was too short to be effective.

Sand Movement.—More than half a century ago, Sir John Coode, in his capacity as consultant engineer for the proposed harbour works at Fremantle to be built for the colony of Western Australia, came to the conclusion that there was considerable sand movement across the mouth of the Swan River and that the essential movement was from north to south. This opinion was supported to a large extent by C. Y. O'Connor, who was the principal engineer responsible for the design and building of Fremantle Harbour, though he considered that the movement of sand was not as great as Coode had suggested. It has long been recognised that there is a movement of sand along the coast in both directions at certain seasons and in certain weather conditions (to be discussed below) but it is the *net* transport of sand that is significant.



Text fig. 4.

The coast from Fremantle to Cottesloe as it was surveyed in 1874. Compare with Text fig. 5, which shows the coast as it was surveyed in 1947. Note the conditions existing in the mouth of the Swan River prior to the building of Fremantle harbour.



Text fig. 5.

Map of the Fremantle-Cottesloe area, as it was surveyed in 1947. Compare with Text fig. 4 showing the same area as it was surveyed in 1874.

Since the building of the moles and other engineering works, it has become apparent that the main movement of sand is the reverse of the direction suggested by Coode and O'Connor, *i.e.*, south to north. If the movement of sand had been north to south, then Cockburn Sound would have silted up rather than have two banks formed across the northern end of the Sound. Rather, it is suggested that the banks were formed from sand derived from beaches along the west coast south of Garden Island. This sand, having been worked to the north by wind and wave action around Garden Island and Carnac Island, is then distributed towards the east, across the north end of Cockburn Sound in two parallel sand banks. The exact nature of this movement is not clear, but from the evidence of the formation of the tombolo to Point Peron (Fairbridge, 1950), it seems fairly certain that the principal migration of sand along the west coast of this State is from the south rather than from the north.

If the sand movement is in this direction, as suggested above, there is a sand supply continually coming into the area. This sand has not only built up the area around South Fremantle and Fremantle itself, as already mentioned, but prior to the building of the moles also supplied sand to the area to the north.

To the north of Fremantle the sand movement is along the beach in accordance with the seasonal variations, and subjected to the normal action of beach conditions. There is no evidence that there were major areas of accumulated sand before the time when the North Mole was built. As in the southern area the net sand movement is in a northerly direction.

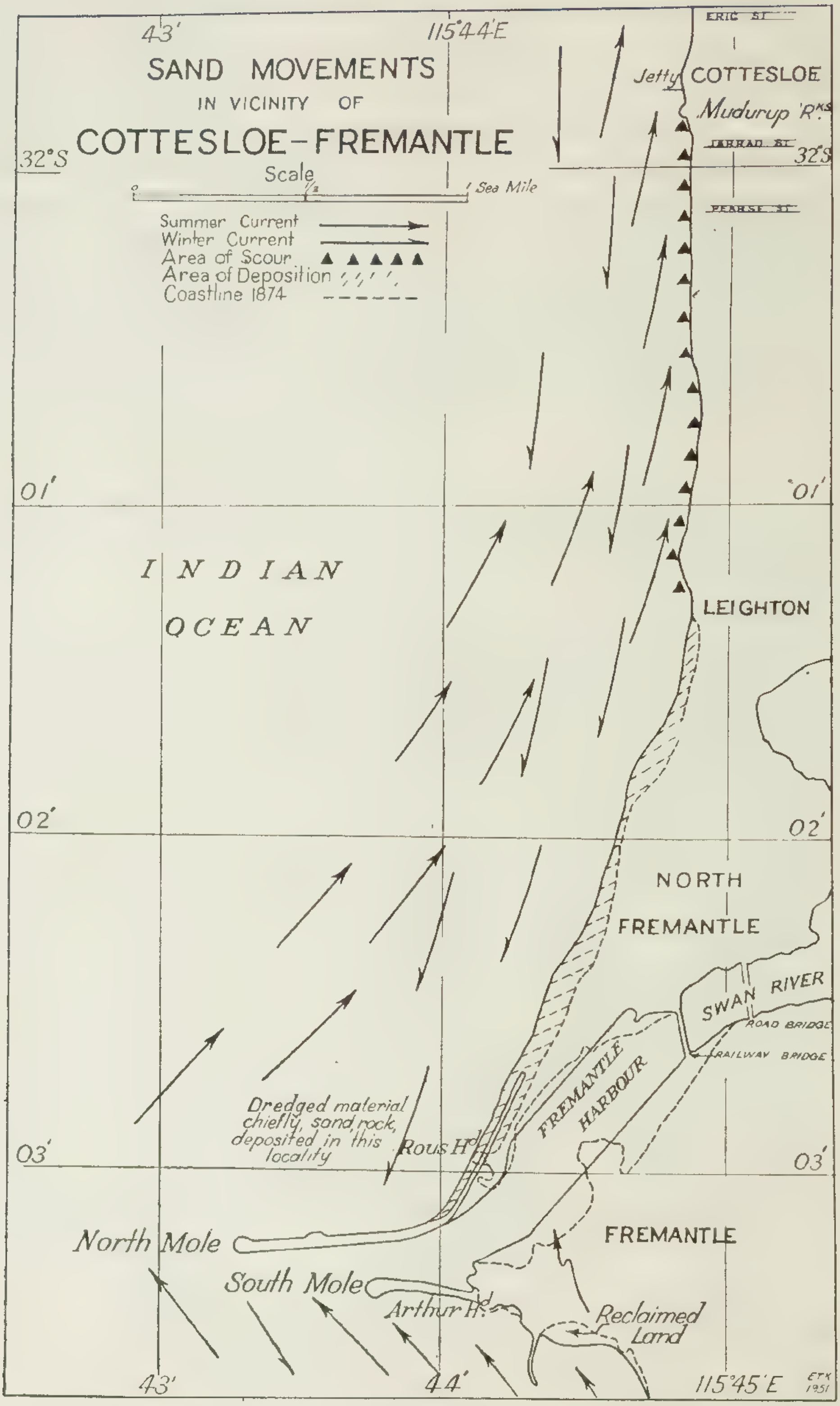
So far, in this discussion, the effect of the moles at Fremantle has not been taken into consideration. With the building of the moles two "shadow" areas were formed. When the currents are moving north a section of the coast from Leighton to the base of North Mole is protected. When the currents are moving south a corresponding section of the southern coast is protected.

In the area north of Fremantle, the winter conditions drive the sand south into the protection of the moles depositing it against the North Mole, or in its immediate neighbourhood. This sand would formerly have been carried south past the heads before being returned by the summer conditions.

With the summer conditions, the coast north of the Mole, as far as Leighton, is protected, thus not giving up any sand to replace that eroded farther north along the coast in the winter. South of the moles erosion is taking place because of the failure of the summer conditions (causing sand deposition) to compensate for the erosion of the previous winter. The result has been a large accumulation of sand between Leighton and North Mole and an eroded beach between Cottesloe and Leighton.

The above remarks are generalisations. Local observations at appropriate points seem to bear them out fairly consistently. In the south (Cockburn Sound area), there is very little silting in progress. The Parmelia Bank is almost stable and does not show any tendency to deposit sand along the shore, either to the north or to the south of the bank. A spit has built out parallel to Parmelia Bank at right angles to the trend of the shore ; a wooden groyne put in near this spit does not show any accumulative deposits on either side (*i.e.*, according to the Chart AUS. 077).

At South Fremantle Power Station there is a strong southerly drift during the N.W. winds. As the S.W. winds have only a limited fetch they do not produce a strong drift to the north, with a result that erosion takes place at Pt. Catherine.



Text fig. 6.

The Fremantle-Cottesloe area showing the dispositions of the summer and winter currents, the areas of accumulation and erosion of sand since the area was mapped in 1874. Most of the changes around Fremantle are reclamation for Harbour works and town sites, but north of the North Mole the changes are due to wave and wind action.

North of the mole there is an accumulation of sand between North Mole and Leighton Beach, an erosional scouring of sand between Leighton and Cottesloe, and from Cottesloe to the north there is a more or less even balance between summer and winter conditions.

Other beaches along the coast to the north show varying characteristics. Swanbourne Beach has not changed materially in 15 years since the Surf Life Saving Club was built, according to the Club's president.

At City Beach, from information supplied by Mr. J. Edwards of the City Engineer's Department, the net variation in the high water mark in several consecutive years formerly showed a loss by erosion of 14 feet annually. The erosion was also about the same rate at the storm water outlet from Herdsman Lake. This outlet is some three-quarters of a mile north of City Beach. When the City Beach groyne was built about 1935, however, the erosion stopped not only at City Beach but also at the storm water drain.

The effect of a groyne here was satisfactory, as predicted by the engineer, who had observed that in this area there are two distinct sets of currents, one a northerly current during the summer which was much stronger than the southerly current which was active during the winter. The relative strength of the currents can be inferred from the fact that the sand on the south side of the groyne will build up to a maximum in a shorter time than it will build up on the north side. In fact, the maximum accumulation of sand on the north side requires at least 4 days of continual strong north-west winds.

The precise reason why it takes 4 days to reach maximum accumulation on the north side of the groyne is not perfectly clear. Many factors come into such considerations. For instance, if the sea was very rough and the waves were breaking beyond the end of the groyne, as may happen in very rough weather, then the normal action of the sand movement by waves would tend to by-pass the groyne. If the wind were to shift a few points north of west, it is quite likely that a rip may be set up on the north side of the groyne, thus carrying sand out to sea and defeating the purposes of the groyne.

Observations of the effect of the groyne during a strong S.W. gale show that the area of scours beyond the groyne is situated approximately 300 to 400 yards to the north. It is felt by the City Council engineers, that if the groyne were extended then serious scouring would take place north of the groyne. The scouring at present is not very noticeable, although a few years ago erosion almost undermined the roadway in that area.

At Scarborough, from information of old residents and other observers, the beach is slowly building up. No official information is available concerning the beaches north of Scarborough, but from the reports of various people interviewed, it is not likely that any serious erosion is taking place there.

No attempt has been made to deal with the conditions in Fremantle Harbour, as it was considered that this would necessitate some specialised study. In the investigations to date the influence of the river on the beach erosion and movements of sand does not appear to be important.

III. WEATHER, CURRENTS AND TIDES.

(1) *Weather.*

Daily weather bulletins provided values for the wind strength and direction for Fremantle, Perth and Rottnest. The figures for Fremantle were used mainly, as this station is only three miles along the coast from Cottesloe, although Rottnest, being some 10 miles offshore, gives a better indication of the conditions out to sea.

During the beach observations the wind velocities were estimated, using the Beaufort Scale. It was found with experience that the estimates were reasonably accurate when compared with readings for Fremantle. The wind systems experienced along the west coast of Australia are described in the "Australia Pilot" (Vol. 5), and more recently have been co-ordinated in an "Atlas of Climatic Charts of the Oceans" (U.S. Dept. of Agriculture, 1938), where the average wind for each month has been calculated over a unit area of approximately five degrees of longitude by five degrees of latitutde. The information was compiled from ships' logs collected over many years.

From November to March, inclusive, the summer months, the dominant winds are the local land and sea breezes. The force of the land breeze rarely exceeds two on the Beaufort Scale, blowing from the east and south-east. Being an offshore breeze this has a pronounced damping effect on the ocean swell. During anticyclonic conditions, when the wind blows from the east for several days without change, the sea is usually reduced to a state not unlike the proverbial "mill pond." The sea breeze, on the other hand, is a wind often blowing with Beaufort force 3 or greater. Its direction is predominantly from the west and south-west. This breeze builds up considerable waves in the form of a short choppy sea with every wave a "white horse." On an average summer day the land breeze blows from about 3 or 4 a.m. to about midday, then there is a sudden reversal in direction and generally by 1 p.m. a strong sea breeze will be blowing. This "breeze" will blow strongly until about 6 p.m. then die out to almost still air by midnight.

April is a month of indefinite and variable wind conditions with the the possibility of an early winter storm. From May to September there is a period of winter storms alternating with near calms. These storms are up to gale force with north-west and west winds backing to gusty south-west winds. September only has occasional storms, and October is again a month of mild indefinite winds.

It is apparent then that the period of most consistent and steady winds is during the summer months rather than the winter. The effect of the summer winds is therefore dominant and particularly the more powerful "sea breezes."

(2) *Currents.*

Schott (1935) has compiled a map of the Indian and Pacific Oceans showing the distribution of ocean currents for the months of August-September and February-March. These maps show a south moving current off the west coast of Australia for the winter period, and for the summer period a north moving current with a south moving swirl next to the coast. However, these movements are ocean currents and do not necessarily correspond to the directions nearest to the coast. For instance, the sea breezes mentioned above would have very little effect on the ocean currents, as they are restricted to a belt only up to 20 miles wide.

Study of the surface drift from bottles released over the continental shelf by the C.S.I.R.O. Fisheries Branch (by courtesy of Dr. Serventy), show that generally off the Western Australian coast from Bunbury to Geraldton, there are two dominant sets. One is a relatively strong northerly set being effective from September to April of the average year, whilst the other is a southerly, but weaker set, running from June to July and sometimes into August.

During May and August-September, the drift is changeable as are the winds during these two periods. The above results are for an average year and should serve only as a general guide as to what may be expected. There

is in fact a great variation in the figures from year to year and with varying seasons. In the year of study (1949) it was thought that the drift changed from south to north in November, as it was not until then that sand started to move north.

(3) *Tides.*

The tidal effect at Cottesloe is very limited in that the total variation on a daily range averages only about 18 inches. It is fortunate that the nearest tide recording station is only three miles away at Fremantle, and as conditions are very similar the figures may be taken as closely indicative of those for Cottesloe. Bennett (1939) summarised the tidal conditions at Fremantle. Fairbridge (1950) gives the following summary of tidal conditions: "Mean sea-level there was determined in 1933 at 2.27 feet above datum (fixed by harmonic analysis at lowest low springs); the annual range of mean sea-level however, was found to be 1.26† feet. The neap range is about one foot and the mean spring range about three feet . . . . However, with the annual swing of mean sea-level, we get an overall mean spring range of something over five feet."

As pointed out by Curlewis (1916), meteorological conditions also exert a profound influence on tides, high pressure systems, keeping the level low, and cylconic (low) systems keeping the level high.

The highest recorded tide at Fremantle is 6.25 feet (in 1920) and the lowest was minus 0.5 feet (in 1896). However, the physiographic effect of such abnormal tides does not appear to be important.

It is considered by the writer that as the daily variation of tide is so small, then the area can be classed at almost "tideless," *i.e.*, the effect of the tide in relation to other factors, such as waves, etc., can be neglected.

IV. OBSERVATIONS AT COTTESLOE.

The engineer, Sir Benjamin Baker, once said "Nature never deceives you, if you watch her long enough." It is hoped that the year spent observing the effect of Nature's forces on the beach at Cottesloe was long enough to give a sufficient knowledge and understanding of the inter-reaction of the wind, wave and sand, in order to give a reasonably clear picture of the problem and to suggest a satisfactory treatment.

In dealing with Cottesloe in particular, it is proposed to consider:

1. The changes observed during the course of this year's observations, *i.e.*, Diurnal and annual changes,
2. the change over the years from a good beach to a poor beach, *i.e.*, progressive changes,
3. the causes of the changes that have taken place, as indicated by the evidence available.

(1) *Diurnal and Annual Changes.*

A brief discussion of the terminology and process of beach erosion is needed as an introduction to this section.† Many authors have recognised that during periods of storm the sand beaches are flattened and the sand

* There appears to be a misprint in Bennett's paper stating that is 2·26 feet.

† *See* Johnson (1919), Shepard (1948) and Kuenen (1950) for shore-line characteristics and terminology.

moves seaward tending to form a bar at the plunge line. The sand may move out in two ways ; it may be carried out

(i) by rips,

or (ii) by the resultant backwash of the waves.

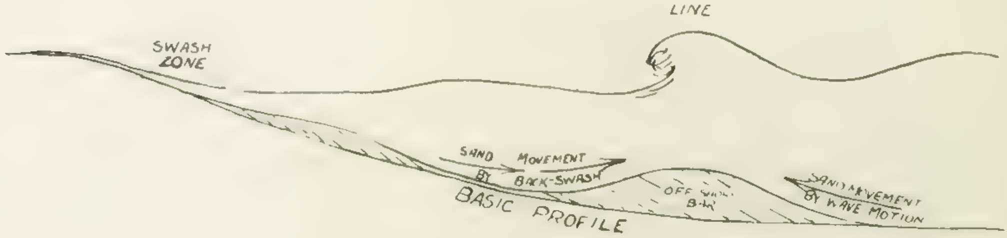
(i) Transport by Rips : Rip currents are defined as seaward moving currents of water which return the water carried landward by waves (Shepard, Emery and La Fond, 1941). It is considered by O'Brien (1950), Inman (1950), Horrer (1950) and Monk and Traylor (1947), that wave refraction concentrates the energy of the waves onto one section of the coast (dependent on bottom contours) and from the centre of that section the water returns to the sea in the form of a strong current or rip.

The workers at the Scripps Institute favour this explanation (*i.e.*, rip currents) for the bulk movement of sand out from the land during periods of strong onshore winds. Such currents attain a considerable velocity and transport appreciable quantities of sand. They are the true rip currents and often correspond to the so-called " undertow " that is commonly reported on many beaches. In general, the rips tend to form in the centre of the bays and have feeders parallel to the shore. The general direction of the current is at right angles to the beach. Sand carried in the scouring current is usually deposited again within 400 yards of the beach, *i.e.*, about twice the distance of the plunge line from the beach.

The sand of the sand-bank which is formed as a result of the rip depositing its load offshore, is subsequently returned shorewards by the normal action of the oscillatory waves after the rip current has ceased to flow.

Rips have also been noticed when there is little or no wind. One was seen at Cottesloe this year during a calm period when a heavy swell was running. This rip was very strong and persisted for more than 24 hours. The wind at the time was a very light E.S.E. breeze. On many occasions rips were seen at Cottesloe long after the wind had died down, but before the heavy swell of a storm had subsided.

(ii) Transportation by Backswash : When a wave breaks, the bulk of the water moves forward in a translatory motion. With the advent of the next wave, the swash of the last wave moves back to the plunge line bringing sand part of the way with it. If the backswash is stronger than the swash, then the sand gradually moves out towards the plunge line. Offshore from the plunge line, sand is moving landwards with the normal oscillatory motion of the waves. Thus, there are two forces moving sand towards the plunge line, each reaching maximum movement at the plunge line. This brings about the building of a sand bar (*see* particularly King and Williams (1949)), in a paper on the formation and movement of sand bars in a tideless sea).



Text fig. 7.

Diagrammatic sketch of the building of an offshore bar.

A sand bank built on the basic shore profile will only remain stationary whilst the height of the top of the bank above the basic profile is less than half the depth of the water above the bank. Thus, when a heavy sea is running, the sand from the beach is moved into a sand bar at the plunge line. But when the sea subsides and the depth of water above the bank becomes less than twice the height of the bank above the basic profile, then the bank is moved shorewards. That is, as the plunge line moves towards the shore, due to the subsidence of the swell, the offshore bar will also move with the plunge line. If the swell subsides so much that the waves are breaking close to the shore, then the bar will not form again but the sand will mount up onto the shore to form a " swash bar " or " whale back."

Grant (1943) recognises a similar occurrence at LaJolla, California, after storms. Bars are formed parallel to the shore during the storm, but after the storm these bars are moved towards the land. There is selective transportation of the sand by the waves as these bars are moved landwards (*see* also La Fond (1940)).

The conclusion may be drawn that with a strong onshore wind or in storm conditions, the actual beach is being eroded or retrograded, but in the relatively calm period after a storm or during an offshore wind, the beach progrades or builds up.

* * * * * * *

At the beginning of systematic observations at Cottesloe (first record, 27–3–1949) the beach was in a very bad state. The sea bed from the plunge line outwards was rock, and for the most part, bare of sand. In the southern portion of the bay a large area of rock was exposed along the beach. During the afternoon of 27th March, a strong sea breeze blew from the south-west with a Beaufort Scale force of 3. In an area just south of the jetty to just north of the jetty, sand was eroded rapidly and transferred north towards the northern limits of the bay. Rocks were uncovered in front of the bathing pavilion. An inspection of the beach next day, when an east wind was blowing, showed that a considerable part of the sand eroded 24 hours previously from near the jetty had been deposited in the north near the northern reef between the plunge line and the shore. The rocks in this area were covered by two to three feet of sand.

These events are interpreted as follows : it is apparent that the beach has been previously exposed to a sea that was nearly calm, due to an offshore or land breeze, and the beach had built up to such an extent that the slope of the swash zone was steep (in the vicinity of 1 in 6 or greater). The strong sea breeze blowing in from the S.W. drove the oblique waves onto a shore that was only stable for a land or offshore breeze. The altered condition produced a change in equilibrium so that the sand was moved back into the sea, tending to build up an offshore bar. However, the longshore drift set up by the oblique waves was so strong that it moved the sand in a northerly direction. Next day, with a return to land breeze conditions and the working of sand onto the shore by the action of the oscillatory waves, there was a building up of the beach some distance to the north of the point of erosion. The above sequence was eventually found to be most typical of events during the summer season.

Text fig. 8.

The beach immediately in front of the bathing pavilion on the 28th April, 1949. The photo was taken looking north from the wooden groyne at the base of the jetty. Note the rocks exposed at (1) and the foundations of the sea-wall exposed at (2).

Text fig. 9.

Looking north from Mudurup Rocks along the beach at Cottesloe as it was on April 28th, 1949. (1) Rock exposed by erosion. (2) Wooden groyne built in an attempt to stop erosion. (3) Rock exposed by erosion some 300 yards north of the jetty.

Text fig. 10.

[illegible] together with the other two piles visible, once supported the north side of a shark-proof swiming area, (9) the 5-ft. bench at [illegible] 1949.

At the beginning of the next summer season (November-December, 1949) the process described above was seen to be repeated many times, so that by the end of the year the beach was again retreating rapidly in the south (*i.e.*, between the jetty and Mudurup Rocks), and was being built up in the north in the vicinity of the north reef. Almost the entire beach was terminated by a steep cliff of sand on the sea side, so fast had the erosion been.

The sea breeze of 27th March was followed by a long period of rather calm conditions with light west, south-west and south-easterly winds. All the sand moved on the 27th March was worked back onto the beach, so that the rock bottom was again exposed.

On 27th April a north-west wind of gale force blew, which persisted for more than 24 hours. The resulting seas attacked the beach in the north spreading sand over the bottom of the bay, building an offshore bar, moving some sand into the southern end of the bay, and building up the beach just south of the jetty. After the gale had blown itself out, a light south-easterly wind blew for several days. This built up the beach along the length of the bay with the exception of the southern 150 feet or so, which remained a rocky beach for nearly all the year.

This type of cycle was repeated on numerous occasions during the winter. In the latter half of June it was noticed that strong rip currents were flowing from a constant point on the beach, just south of the jetty. Erosion of the sand was very active south of this point but not at all to the north. Moreover, seaweed and other drift material was accumulating to the north but not in the south. It was from this position that a strong rip was seen to be running during calm weather with a very light (Beaufort 0–1) offshore breeze blowing. This rip must have had a minimum velocity of two to three knots, persisting for 60 to 70 yards past the jetty in a north-westerly direction.

These rips prevented the beach from building up in the extreme south. It was only after the rips ceased that sand started to accumulate in the south, being assisted by the north-west winds working the sand down from the north and with the help of a southerly moving longshore current. The reef (Mudurup Rocks) then acted as a groyne, preventing the sand from leaving the bay. During the periods of quiescence the sand was built up on the beach as a swash bar. This beach in the southern part of the bay began building about 23rd August, and reached a maximum width about 8th November.

During the last few weeks of November, the summer season of strong sea breezes set in again and the beach began to be eroded to the south of the jetty. The initial erosion by the south-west wind at the close of the winter took place between a point about 50 to 60 feet south of the jetty to a point well north of the jetty. The first few strong south-west winds did not seriously attack the beach, and it was about 10 to 14 days before the beach began to be eroded under the influence of a south-west sea breeze. This lag in the initiation of erosion I believe was due to the presence of a south-moving longshore drift. It is only after this drift is stopped or reversed that erosion, due to the sea breeze, becomes effective. Another point is that up to a week before the erosion in the south became apparent, every north-west wind had been building the beach up to a considerable extent.

In conclusion, it may be said that the net effect of the north-west wind was to move the sand from the north to the south. Early in the year it appeared as though the beach was suffering destruction by the north-west

wind, but this was due to the sand being spread out over rock bottom and being built into an offshore bar. As there was insufficient sand to build a bar to the maximum height of equilibrium for the particular set of waves, the beach was left bare of sand.

Text fig. 11.

The beach at Cottesloe looking north from Mudurup Rocks on 14th October, 1949. This photograph shows the beach as it was just prior to the commencement of erosion by the summer sea breezes.

From the presence of rips in the southern part of the bay it appeared to take up to two months after the end of summer sea breezes to reverse the strong south to north longshore drift. Once this reversal had taken place, then rapid accumulation of sand resulted along the whole of the beach, particularly in the extreme south of the bay.

(2) *Progressive Changes.*

Little evidence can be found in the way of photographs, paintings, etc., on the state of the beach at Cottesloe prior to the building of the bathing pavilion. Undoubtedly a good beach existed, according to all verbal reports, the present beach being a mere shadow of its former self. Both from the verbal reports of many people and from the observations during 1949, it would appear that the disappearance of the beach has been gradual, only becoming very apparent over the last 10 to 12 years.

From the general discussion of sand movements in the Fremantle area, it was apparent that the building of the harbour moles formed an effective blockage to the northward movement of sand. As the sand supply from the beaches between Cottesloe and Leighton was diminished, due to erosion without seasonal replacement, the rate of erosion of the beach at Cottesloe was accelerated until the present state of affairs was reached.

The year of observation (1949) was to some extent unusual in that almost no winds south of west were recorded for two or three months during the winter season, thus giving the north-west winds an opportunity to rebuild the

area, so that an excellent beach was re-established by the middle of November. Nevertheless it required only a few weeks of sea breezes then to carry it away once more.

Text fig. 12.

Looking north from Mudurup Rocks. This photograph was taken in 1906 and shows the beach as it was before the improvements, such as bathing pavilion and promenade, were erected. Note the good beach and the presence of high sand hills behind the beach.

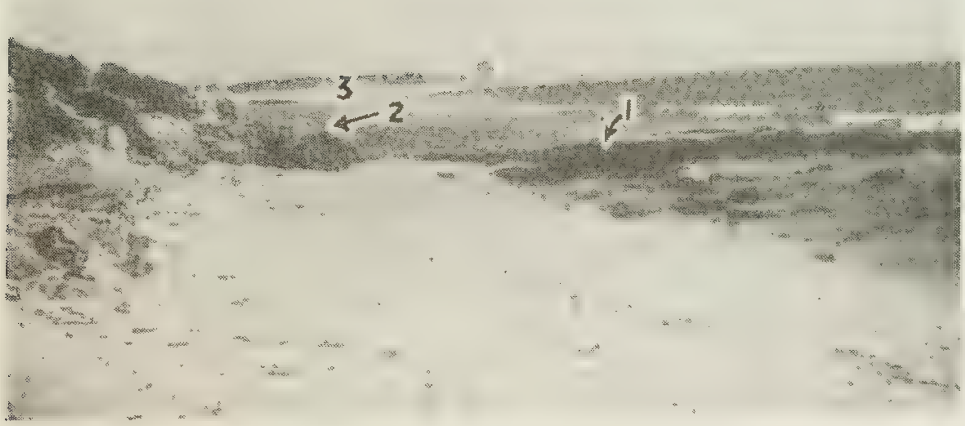
(3) *Causes of the Changes.*

The overall conditions existing in the area both before and after the Fremantle moles were built has been discussed. It is now proposed to deal in particular with the section of the coast from North Mole to Swanbourne. Within this area there is a considerable sector that shows marked accumulation of sand. Another equally long stretch of beach has suffered scouring. These two sections are from North Mole to Leighton (accumulation) and Leighton to Mudurup Rocks (scouring) respectively. North of Mudurup Rocks the beach suffers seasonal variation in the amount of sand being scoured and deposited but no apparent net change.

It was suggested by the writer (Kempin, 1949) that the sand immediately to the north of the North Mole was derived predominantly from dredgings that had been and are still being dumped in the sea west of that area. This view is still held. Somerville (1945) suggested that the accumulation of sand north of the mole was due primarily to the erosion of the beaches around Cottesloe and secondarily to the dredgings from Fremantle Harbour. Hall and Herron (1950) tested the idea that a beach could be built up by dumping dredgings out to sea near Long Beach, New York, but their results were inconclusive. Over the period of their observations (12 months) there was no evidence to prove whether the sand was moving or whether it was settling. The sand dumped off North Fremantle, however, has had some 50 to 60 years to work in to the shore as against only one year at Long Beach.

Certainly much sand from Cottesloe is now on the beaches in the North Mole area, but the volume of sand accumulated here is far greater than the volume of sand eroded farther north. Nevertheless, the observations still indicate that the main movement of sand is northwards. Thus, it is only the sand that moves south in the winter time into the prograding "shadow" area of the mole that is retained. At first, it was thought from the nature and extent of the accumulated sand here, that any drift from the north could be discounted on the grounds that the sand accumulation did not encroach along the groyne. But the groyne was specifically designed by C. Y. O'Connor in such a manner as to defeat such a movement or encroachment of sand; it is not built at right angles to the coast, but is directed W.S.W., and it is carried out into six fathoms of water.

Regarding the eroded beaches north of Leighton, from a comparison of their present state and a description of Cottesloe as it was about the turn of the century by Somerville (1945), it is apparent that erosion has been very active. Further, it is clear that it is only the old beach that has been eroded and very little erosion of the sand hills at the back of the beach has taken place. An examination of the coast between Swanbourne and Leighton shows that almost the entire beach over this distance is underlain by a rock bench. In places this bench forms a contemporary wave-cut platform which is horizontal at about low water mark, in others it forms a bench three or five feet above datum. At Mudurup Rocks is a contemporary wave-cut platform or bench, but the rocks at the foot of Jarrad Street are part of a 5 ft. bench. From Pearse Street to Leighton a 3 ft. bench is almost continuous.



Text fig. 13.

Looking south from approximately the foot of Pearse St., Cottesloe. This photograph shows a typical beach for that part of the coast from Mudurup Rocks to Leighton. (1) 3-ft. bench exposed by erosion of the beach. (2) Coastal Limestone outcrop on the beach. (3) Good "built-up" beach just south of Leighton. In the background can be seen the wheat silo and some of the harbour installations of Fremantle

Since these are platforms of hard rock, then the sandcover over them could never have been extensive. For this reason it is held that only a small amount of the sand north of the Fremantle mole has come from the Cottesloe area. Mudurup Rocks and the various rock benches have also saved the sand hills behind the beach from erosion because they break the force of the waves and reduce their destructive power.

With the stripping of the beach between Mudurup Rocks and Leighton, the northerly longshore drift moving around Mudurup Rocks into the bay of Cottesloe is " barren " of sand. Thus, it is not surprising that, with a longshore drift from the south, the beach at Cottesloe disappears rapidly as no sand is being brought in to replace that eroded.

Towards the end of summer, when Cottesloe beach has been nearly eroded away, the effect of this " barren " littoral drift begins to be felt farther north at Eric Street Pool and along the coast almost to Swanbourne.

During the winter the Mudurup Rocks act as a groyne to the southerly drift, so that the sand builds up in the bay. However, because the summer conditions are so effective in removing the sand from the bay, winter conditions never build up sand against the " groyne " to its maximum capacity. If the bay were filled up to its maximum, then sand would travel around Mudurup Rocks and tend to replenish the beaches farther south. As one proceeds north the effect of the North Mole on the movements of beach sands becomes progressively less until, in the vicinity of City Beach, it is negligible.

V. CONCLUSIONS.

From a broad study of the unit area from Cockburn Sound and Fremantle to Scarborough, the general seasonal movements of sand have been ascertained. These movements are closely linked with the directions of the surface drifts associated with the prevailing weather cycles. During the summer months the surface current is in a northerly direction due to the main winds coming from the south-east, south, and south-west. It is during this period also that the northerly littoral drift is observed.

The duration of these currents and longshore drifts (the two are closely connected) is an important consideration in the net movement of the sand. Observations by the C.S.I.R.O. Fisheries Division show that the north-moving current flows for approximately 8 months of the year (September to April inclusive), whilst the southerly movement is only present for approximately 2 months (June to July). From this a net movement of sand in a northerly direction would be expected, and the form of the coastal features, such as river mouths, headlands, islands, tombolos, etc., certainly does indicate an overall movement of sand from south to north, although observations on actual movement in various localities along the coast show that the amount and speed of movement of sand is highly variable.

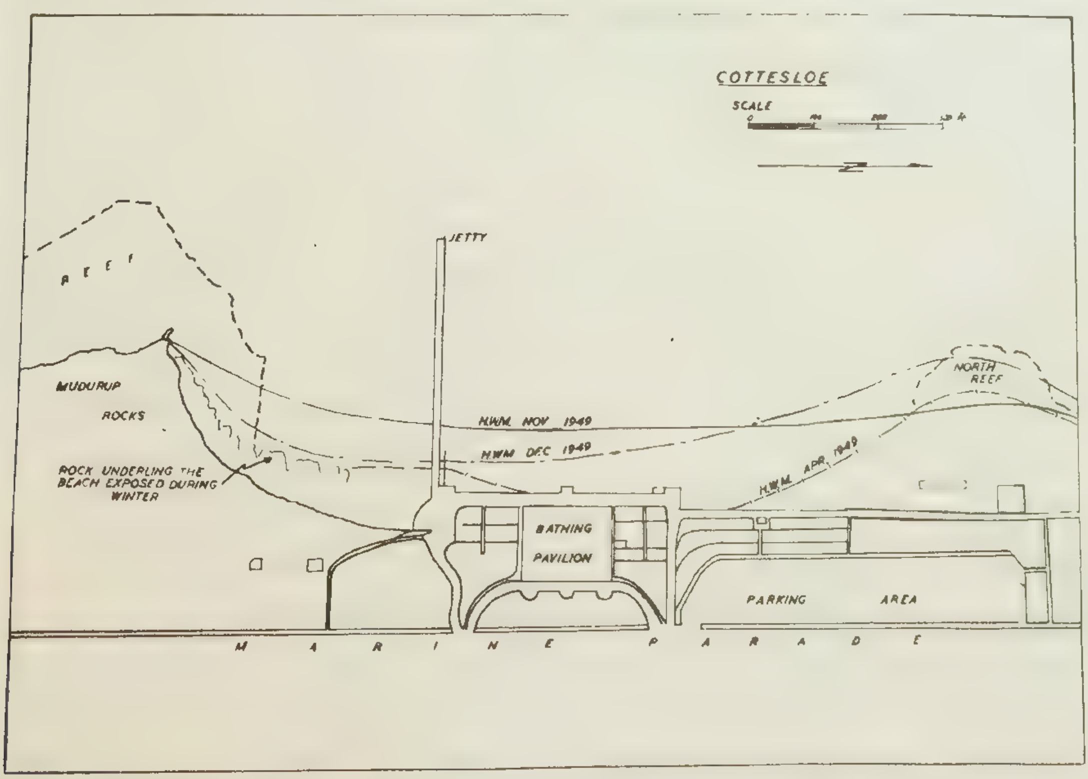
Thus, the conclusion has been reached that the sand movement (in the whole area from south of Point Peron and even possibly south of Mandurah) is in a northerly direction up the west coast of Garden Island towards Rottnest Island. As the sand moves north past Garden Island, part is carried to the east past Carnac Island, forming two large east-west submerged ridges of sand known as Parmelia and Success Banks. This east-west orientation of these sandbanks appears to be due to the action of deep sea swell coming in through openings in the north-south chain of reefs between Garden Island and Rottnest. As stated previously, this explanation is only tentative, but it is certain that the source of the sand is from the south. The constitution

of the sand, being very fine and over 90 per cent. carbonate, suggests that it is the fine fraction from beaches. The general type of sand agrees closely with the average sand from Garden Island.

The inner part of the Parmelia and Success Banks merge with the coastline and have clearly caused large quantities of sand to be deposited in the immediate vicinity of South Fremantle and Fremantle itself. Old drawings of Fremantle show the site of the town as a low-lying tombolo that had built up from the south. South Beach itself is a " reclaimed " or " built up " offshore bar. It seems quite likely that the mouth of the Swan was displaced northward until it took up its present position, and, before the harbour works there, it flowed over a rock bar.

North of Point Rous the northward movement of sand before the groynes were built was probably not very noticeable. Here, in fact, the movement may have been rather well-balanced (to the north in the summer and to the south in the winter). However, after the building of the North Mole had interrupted the normal longshore drift, both the dumping of dredgings and the southerly drift of sand along the shore caused sand to be trapped and a large deposit was formed between here and Leighton. The dredgings no doubt account for the large quantities of rock debris that is found along the beach here. The mole thus formed has a " shadow effect " on the northward-moving drift and causes strong wave refraction in towards the shore.

At Leighton Beach the " shadow effect " and refraction of the mole ceases, and from here northwards the northerly longshore drift sweeps the coast all through the summer season. As it comes into the coast devoid of sand, scouring begins once more until a full load is being carried. Over the years the combined effort of the southerly drift moving sand into the " shadow area " behind the mole, and the scouring of the beach by the northerly current, has stripped the beaches between Leighton and Mudurup Rocks of all available sand.



Text fig. 14.
Shows the position of high water marks (H.W.M.) at various times of the year. (Note: - The change in position of H.W.M. from November, 1949 to December, 1949. This clearly shows the effect of the sea breezses in moving sand northward.

At Cottesloe it is found that the reef out from Mudurup Rocks is acting as a low groyne, preventing the sand moving south past this point under the influence of the south-moving winter drift. In summer the northerly drift, which is running from an area where sand is not available (*i.e.*, Leighton-Mudurup), enters the bay at Cottesloe and erodes the beach here. The winter-accumulated sand is thus the first beach which is capable of supplying material, and in early summer yields large quantities of sand which is moved northward. When Cottesloe has been stripped, the scouring action moves northward.

Farther north the supply is sufficient to meet the demand, so that erosion is not very apparent, although at City Beach some erosion was taking place until a groyne was built which stabilised the coast to a very large extent.

The recommendations made at the conclusion of the survey were that as the sand is brought into the beach at Cottesloe during the winter months, the problem is to keep it there during the summer, and to this end the construction of a groyne was suggested. The site of this groyne would be Mudurup Rocks in such a direction as to cause the " barren " summer northerly drift to be deflected from the bay and to stimulate wave refraction to maintain the beach in a manner analogous to that observed at Leighton.

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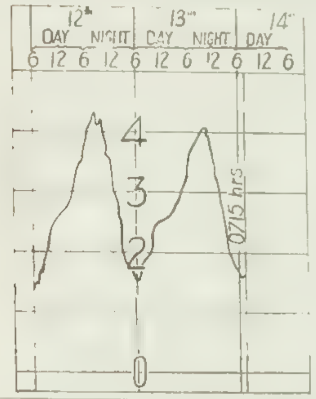
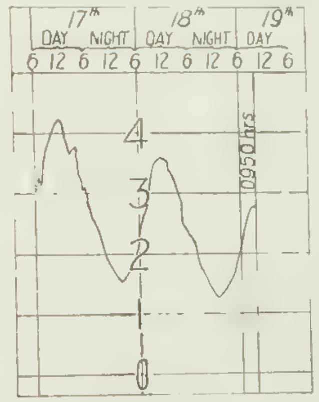
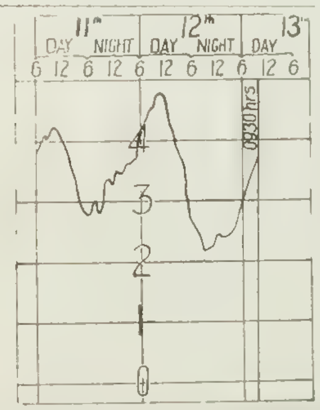
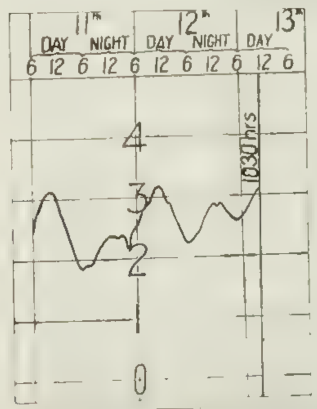
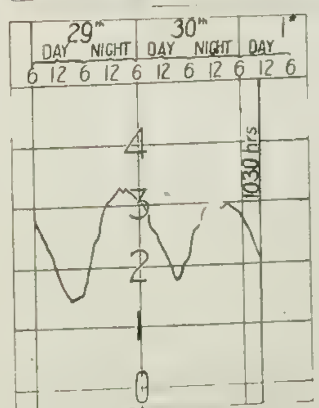
APPENDIX 1.

Details of Aerial Photographs taken during the year 1949, together with Tide and weather conditions prior to the runs.

N.B.—Tide in feet above Fremantle Harbour Trust Datum (approx. : 1 foot below Admiralty Chart Datum i.e., M.L.L.W.S.).

Run.	Date.	Time.	Height of Plane.	Focal Length of Lens.	R.F.	Tide for Previous 48 hours.	Winds for Previous 4 days.
1	14–2–49	07·15 hrs.	3,960 ft.	5 inch	1 : 9600	 FEBRUARY	The winds were mainly E. to E.S.E. with a Beaufort Force 2–3 except during the afternoon of the 13th February, when a W.S.W. wind blew for 4 hours. Wind at 0715 on 14th February was East, Beaufort Force 2.
2	19–4–49	09·50 hrs.	1,500 ft.	7 inch	1 : 2570	 APRIL	For 15th to 17th April, inclusive, the winds were N. to N.N.W. later backing to W. and S.W. with average Beaufort Force 3–5. On 18th April the wind was variable from N.E. backing to W. to S.E. Average force ÷ 1. Wind at 0950 on 19th April ÷ S.E. Force 2.
3	13–7–49	09·30 hrs.	1,500 ft.	5 inch	1 : 3600	 JULY	For 9th July wind was S.S.E. veering S.S.W. force 4. On 10th July wind predominately E. force 2. From 11th to 12th wind backed from N.N.E. to S.W. with mean force 4. Wind at 0930 on 13th July N.E., force 2.
4	13–8–49	10·30 hrs.	920 ft.	7 inch	1 : 1500	 AUGUST	For 9th Aug., wind backed W. to W.S.W. force 4. On 10th wind N.E. backing to N.W. with force 2. On 11th wind N.E. backing to S.W. force 2, and 12th wind N.N.E. to W.N.W. force 2. Wind on 13th August at 1030 W.S.W. force 1.
5	1–10–49	10·30 hrs.	3,960 ft.	5 inch	1 : 9600	 SEPTEMBER-OCTOBER	For 27th September wind N.W. to W. force 3, the 28th September, N.N.W. to W. force 4, 29th September, W. to W.S.W. force 4, 30th September N.W. force 4, later backing to S., force 2. 1st October at 1030 S.E. force 2.

3.—PHYSIOGRAPHIC AND OTHER NOTES ON A PART OF THE SOUTH COAST OF WESTERN AUSTRALIA.

By

E. de C. Clarke and H. Tarlton Phillipps.

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CONTENTS.

ABSTRACT.

The paper discusses a strip of country, and the adjoining sea, stretching along the coast for about 600 miles, from Long Point to Israelite Bay, and extending inland from a few miles to about 50 miles. A general description of the area, its economics, and early settlement is given, including some mention of mining operations in the Ravensthorpe District, and the building of the first overland telegraph line from Adelaide to Perth.

Mention is also made of the continental shelf, the adjoining sea-floor, the tides and currents, and the Recherche Archipelago. These islands are basically of granitic rocks, but on some of them this is overlain by Coastal Limestone, which occurs on certain islands over the whole length of the archipelago. It is suggested that it was originally continuous, and probably represents the remains of the original coast of this part of the mainland, also that the formation of the archipelago was a relatively recent event, following the laying down of the Coastal Limestone.

Climate and rainfall are also discussed, and reference is made to a dry cycle, which has apparently affected a portion of the strip, during the last 25 years. After describing the soils and vegetation of the strip, the relationship between the rocks and resultant coastline is shown. The many wave-cut platforms, raised beaches and sea-built flats provide much interesting information about former sea-levels. Mention is also made of some remarkable caves in some of the gneissic hills, including a tunnel through Frenchman's Peak, and it is suggested that their formation may have been contemporaneous with that of the wave-cut platforms of Mt. Ragged and the Russell Range. The various Natural Regions, beaches, dunes, springs, and inlets are also described.

I. INTRODUCTION.

A. Area discussed.

This paper discusses a strip of country, and the adjoining sea, stretching along the coast of the State for about 600 miles from Long Point (about long. 116° 30′ E.) to Israelite Bay (about long. 124° E.) and reaching for distances varying from a few miles to 40 or 50 miles inland. It includes parts of more than one " zone," or " province," or " region," depending on whether it is being discussed from the botanical, agricultural, or geographical standpoint ; we shall, for want of a better term and for the sake of brevity, refer to it as " the Strip."

B. General description.

The strip embraces a little of the Kalgoorlie Region, most of the Stirling Natural Region, and the south end of the Jarrah Region (Clarke, 1927, pp. 121–2, and 1936, pp. xi and xii). The westernmost sixth or so, in the Jarrah Region, composed almost entirely of Pre-Cambrian igneous and metamorphic rocks, stands, on the average, 800 or 900 ft. above the sea, and is, broadly speaking, a plain covered with heath and scrub and crossed by rather shallow but often steep-sided watercourses. Much of this plain is underlain by horizontally bedded sediments—the Plantagenet Beds of Miocene age—through which project hills of the Pre-Cambrian metamorphic and igneous rocks. Most of the hills slope rather gently down to the plain and do not rise more than than 100 or 200 feet above it, but the Stirling, Barren, and a few other ranges, are higher, and are steep and rugged. The plain rises gradually north of the Strip and forms part of the " Great Plateau of Western Australia," the average height of which is probably between 1,000 and 1,500 feet. (Jutson, 1934, p. 4).

Much of the coastline is rocky with many bold headlands alternating with sandy beaches. Behind some of the beaches are shallow inlets, most of which are cut off from the sea and are nearly dry. The sea fronting the eastern half of the Strip is dotted with small islands for 30 or 40 miles southwards ; the islands lying off the western half are few and rather close to the shore.

There is a superficial resemblance between the eastern plain, dotted with island-like hills, and the adjoining sea with its many islands ; but the plain is not all at one level, for in it, in different places, the more or less horizontal surfaces are at different heights above sea-level.

C. Acknowledgments.

From the time of J. S. Roe, the first Surveyor-General of Western Australia, surveyors, geologists, and others who have examined portions of the Strip have described some of its physical features and we shall refer to their contributions later. The physiography of two parts is discussed in detail by Jutson and Simpson (1917) and by Woolnough (1920). Our observations were made when investigating the Pre-Cambrian rocks and we have combined with our notes information from many sources which are all, we trust, acknowledged in the text. We were helped financially by a Commonwealth Research Grant, made available through the University of Western Australia, and we are greatly indebted to Mr. P. Stanley, Chief Draughtsman of the Lands and Surveys Department for the preparation of finished copies of the map and figs. 1 and 16, and to Dr. J. T. Jutson and Mr. E. S. Clarke, who read the manuscript of this paper and made many very helpful suggestions.

D. Historical Notes.

The population of the Strip is about 10,000 of which more than 8,000 live in or to the west of Albany. Perhaps the earliest settlement was at the end of 1826, when Major Lockyer arrived in King George Sound, after a seven-week passage from Sydney, with a small party of soldiers and convicts. It was only in the next decade that much real settlement began. At that time the chief activities were sealing and whaling, for which depots were established at Doubtful Island Bay, Cheyne Beach and Cape Riche ; also several small vessels (of the order of 100 tons) were built. In 1843 Albany's population had grown to 260, and the tonnage of shipping served was practically the same as Fremantle.

In the strip east of Albany, the rainfall is smaller, there are no forests, the soils are generally "lighter," and there has been much less settlement. We are much indebted to Miss M. Lukis, State Archivist, for the following information about settlement in this part.

It is interesting to note that when E. J. Eyre made his overland journey along the coast in 1841, he did not find any signs of settlement until he was within a few miles of King George Sound. When John Forrest made the same trip in the opposite direction in 1870, he did not approach the coast until he had crossed the Phillips River, but along the coastline from there to Eucla, the only two stations were Campbell Taylor's on the Oldfield River and Dempster's at Esperance. During the 70's several others were established and, west of the Oldfield, towards Albany, a number of isolated settlements were already in existence. In most cases it is only possible to give approximately the date of foundation of these stations, as it often happened that applications for pastoral leases were not made until the country had been tried out for a few years.

Warriups Station (about 40 miles N.E. of Albany). This was first taken up by the Wray family in the 70's, but later passed to the Hassells.

Cape Riche. The land in this district was originally taken up by George Cheyne, who however only used it as an out-station. Cheyne also had a large pastoral lease on the *Pallinup River* in 1847. The first permanent home near Cape Riche was set up by Cheyne's cousin Andrew Moir, who went there with his family soon after his arrival at King George Sound in 1844.

Bremer Bay. The first home was established here about 1860 by John Wellstead, who moved there from Albany with his large family. Both George Cheyne and T. B. Sherratt had bases for whaling in *Doubtful Island Bay* as early as 1837.

Jarramongup was originally taken up by Capt. John Hassell, probably in 1849, although there is no record of an application for a pastoral lease in the district by John Hassell until 1851 and the first mention of the name "Jarramongup" is in 1853.

Phillips River. The first settlers on this river were the Dunn Bros., who took up a lease in 1868 and built the old home at Cocanarup, which still stands.

Oldfield River. Campbell Taylor founded a station here in the 60's. In the early 70's he took a pastoral lease of a large area near *Cape Arid* and built the homestead "Lynbourne" on the *Thomas River*, where he lived and brought up his family.

Stokes Inlet and Fanny's Cove. A large pastoral lease bordering on these was taken up by John and Alexander Moir in the early 70's.

Esperance. The Dempster brothers established several stations in this district in the 60's. By 1870 they had settled at Esperance but formerly had a home at Mainbenup, about 25 miles to the west.

Israelite Bay. A large pastoral lease near Mt. Ragged was taken up in 1876 in the name of Stephen Ponton, and there were other leases in the district assigned to Ponton Brothers and Sharp (Stephen Ponton, William Ponton, John Sharp). The first lease of the land bordering Israelite Bay itself was issued in the name of an Albany settler, C. B. G. Heinzmann, in 1874.

Man has made little change in the original state of the Strip east of Albany, apart from a limited amount of settlement round Ravensthorpe, Hopetoun, and Esperance. As a port for the Goldfields, Esperance possesses many advantages, and there is some prospect that recent advances in methods of farming "light lands" may lead to closer settlement and greater productivity in this district.

The Strip has produced little in the way of mineral wealth, except near Ravensthorpe, where indeed there is hardly any mining activity now, but from which, since 1900, have come between eight and nine thousand tons of copper, about 88,000 oz. of gold and 16,000 oz. of silver. At Naendip, near the head of Dempster Inlet, is "an abandoned copper mine, several shafts of which tell . . . . . . of Thomas Sherratt, who in the early 60's steered his cutter 'William and Mary' into Point Charles and landed his party of prospectors" (Stevens,

1933), but we can find no record of the production of copper or any other mineral from Naendip. Manganese ore, graphite, and beach sands containing zircon have been prospected in several places, and about 600 tons of vermiculite have been taken from a formation in the Young River, 76 miles by track W.N.W. of Esperance.

A noteworthy achievement between the years 1875 and 1877, when Western Australia was a colony, was the erection of a telegraph line from Albany to Eucla, whence it connected with Adelaide. Miss Lukis has kindly allowed us to extract the following information from the State Archives :—The originator of the project was apparently J. C. Fleming, Superintendent of Telegraphs, but evidently C. D. Price, afterwards Assistant Surveyor-General, was very largely responsible for its success, for, in July, 1878, the thanks of the Legislative Council were conveyed to him " by the Speaker at the table on the floor of Parliament House " for " running the line " from Albany to Eucla. Although it was abandoned when the line following the Trans-Australian Railway was completed, many of the posts of " The Old Telegraph Line " still stand and are a valuable reference line for the geologist or geographer in this rather meagrely mapped country. The present-day traveller in these parts realizes that Stevens, in his interesting account (1933) of the construction of the line, has passed very lightly over the hardships and difficulties that must have been encountered in those days, when bullocks, camels, and horses were the only means of land transport.

II. THE SEA.

A. Sea Floor.

Information about the sea floor given on Admiralty Chart 2757b " corrected to 14th Dec., 1946 " shows that the 100-fathom line lies south of the coast at distances varying from 19 miles (south of Bald Island) to perhaps 42 miles (south of Cape Pasley), but soundings between Cape Knob and Israelite Bay are too few for this line to be indicated on the chart. Beyond the 100-fathom line or its approximate position, the floor slopes to depths of more than 1,000 fathoms, in most places at angles of 5° or less, but just west of Long Point, at about 20°, and inspection of the chart shows that elsewhere also it is probably steep. Details of shallow soundings near harbours, such as Esperance, show that the continental shelf has a very irregular surface, and Dr. D. L. Serventy (Fisheries Division, C.S.I.R.O.), tells us that its many irregularities make trawling impossible.

Soundings are not numerous enough to prove that any of the river valleys continue across the continental shelf, except the King-Kalgan (Jutson & Simpson, 1917, Pl. 1).

B. Islands.

The continental shelf which fronts the eastern part of the Strip carries many small islands—the Recherche Archipelago—which, together with the very numerous partly or wholly submerged rocks and reefs, are further evidence of the irregularity of the continental shelf. Between Cape Le Grand and Israelite Bay these islands and rocks dot the sea, extending southwards for 33 miles, but west of about long. 121° they are few, and lie close to the shore. Middle and Mondrain are the largest islands, and none, judging from available maps is more than from three to five miles in length or breadth.

The only island which we have personal knowledge is Thomas Island, situated about 7 miles east of Cape Le Grand. It is about three-quarters of a mile in length and approximately 150 feet high. Like many of the other islands, it is composed of gneiss and has no beaches. It is largely covered with heath and carries bushes and the ordinary coastal vegetation in the more sheltered places. Bechervaise (1951, p. 14) says: " All the islands without exception are basically of granitic rock, ... The granite reaches a considerable height on several islands, culminating in the peak of Mondrain (743 ft.). Only a little lower and much more abrupt is Remark (722 ft.) and the Twin Peaks both exceed six hundred feet." Many other heights of over 100 feet are given in " Australia Pilot." The highest of the western islands are Bald (1,020 ft.), Eclipse (400 ft.), Breaksea (384 ft.), Haul-off Rock (314 ft.), and outer Doubtful (246 ft.).

Many of the islands, as seen from the mainland, rise rather abruptly from the sea, but those about 5 miles E.S.E. of Duke of Orleans Bay appear, from a distance, to have platforms which are within reach of storm waves (text fig. 1).

Text Fig. 1.
Profile of islands about five miles E.-S.-E. of Duke of Orleans Bay.
H. T. Phillipps. Photo.

In addition to " granitic rock," Coastal Limestone (Clarke, Prider & Teichert, 1948, p. 286) occurs on a number of the islands of the Recherche Archipelago, from Boxer Id., 15 miles S.W. of Esperance, to Christmas Id., 25 miles S.E. of Israelite Bay (personal communication from Dr. D. L. Serventy). It is generally thought that Coastal Limestone has been formed along beaches where there is an ample supply of calcareous material, and it seems unlikely that conditions for such a deposit would exist along the shores of small islands in a rough sea. If this assumption is correct, then the Coastal Limestone occurrences in the Archipelago must once have been nearly continuous, and, when they have been mapped, it should be possible to link them together, and so reconstruct the once unbroken coastline. There will be some support for this suggestion if the apparent absence of Coastal Limestone from the mainland east of long. 120° E. is confirmed, and it will seem that, when the Coastal Limestones were being formed, the mainland of the eastern part of the Strip extended far south of its present position. It will also be clear that the formation of the Recherche Archipelago was a rather recent event which occurred after the building of the Coastal Limestone.

C. Currents and Tides.

The Southern Ocean near the south coast of Western Australia has been said to have a current moving westwards in summer, eastwards in winter, in harmony with the prevailing winds (see, for example, Gentilli, 1947, p. 19). However, in the " West Australian " newspaper of June 7, 1950, it is stated that " a spokesman of the Fisheries Division of the Commonwealth Scientific and Industrial Research Organisation said that bottles placed in the sea at Albany invariably were found to the east." Supporting this, as Dr. Serventy pointed out to us, " Australia Pilot," Vol. I, Third Edition, 1937, p. 23, states that there is an easterly current throughout the year " following the gen-

eral trend of the outer edge of the bank with depths of less than 100 fathoms," and also that from 116° to 120° E. "the average coastal current sets nearly due east, with an average rate of from 5 to 6 miles per day, throughout the year." "Australia Pilot," however, also refers several times to "reverse currents setting in a westerly direction" and Serventy pointed out (1937, pp. 66–68) that there are many departures from the generalization that the current flows eastwards. Thus, from 24th February to 2nd March, 1930, owing to engine failure, the trawler "Bonthorpe" drifted S.W. "at a rate varying from 12 to 25 miles per day." Serventy considered that these local currents, due no doubt to seasonal winds combined with the configuration of the shoreline, are probably important physiographical agents.

Regarding tides, Capt. A. Eggleston, for several years in command of vessels calling at various places along the south coast, has told us that between Albany and Eucla from January to March, the rise and fall is generally 2 ft. 6 in. but less if strong easterly winds prevail ; from March to June it is 2 ft. 6 in. ; from June to December, if a N.W. gale is approaching, the tide may rise 6 ft. or even more. We are also indebted to Capt. H. Griffiths, Harbour-Master at Albany, for the following statement :—"At Albany, barometric pressure seems to have great influence on the height of the tide. In summer, with high pressure, the tides are low; in winter, with low pressures, they are much higher. The average range at any period is 2 ft. 6 in. to 3 ft. The full effective range is about 5 ft., but a high tide of 5 ft. or so above zero would only fall to 2 ft. 6 in. or 3 ft. above zero, and, if the sea rose from zero, it would only go to about 2 ft. 6 in. There appears to be very little regularity about the tides, but there is one high and one low per day."

III. THE LAND.

A. Climate.

The Strip has a "cool" or "cool oceanic" climate, temperatures in the hottest months (January and February) being seldom above 72° F. The prevailing winds are easterly in summer, westerly with gales in winter. The average rainfall is about 20 inches. Most of the rain falls in winter, June, July, and August being the wettest months, each with about 5 inches (Taylor, 1918, p. 63 ; Gentilli, 1947, pp. 49, 93–104, 108–125, gives more recent data).

There can be no doubt that portion of the Strip, between Albany and Hopetoun, has been passing through a dry cycle during the last 25 years. Throughout that period the water-table at Doubtful Island Bay has fallen about 3 ft. and many of the inlets, which used to be open nearly every winter, have remained closed for ten years or more. In 1937 the Fitzgerald, Dempster, and Hamersley Inlets all contained a large quantity of water. Now all are dry, or nearly so, and at Dempster Inlet large paperbarks, possibly hundreds of years old, bordering the inlet, have perished (text fig. 2). Dr. D. Serventy informs us that between 1915 and 1920 the Hamersley Estuary contained large quantities of oysters and fish, including mullet, black bream, salmon trout, pilchards, flathead, and whiting, which were netted commercially. The estuary has remained closed since 1915, and by 1926–27 all the fish and mollusca had died, and although it has been more or less filled several times since then, it has not been open to the sea.

Text Fig. 2.
Dempster's Inlet in January, 1950. Salt-encrusted flat with dead paper-bark trees, which were alive in January, 1947.
A. Wilson, Photo.

B. Vegetation.

Jarrah forest, and to a small extent karri forest*, occupy the south-west corner of the Strip, i.e., the part which is in the Jarrah Region (Clarke, 1927, pp. 121–2). Gardner (1944, pp. xlii–iii and Pl. X) describes the jarrah forest as "a true sclerophyllous formation, remarkable for the paucity of other tree species," its only associates being *E. calophylla* (the marri or red gum) and *E. patens* (the blackbutt). Between these taller trees is a rather sparse undergrowth of shrubs and small trees, such as wattles and species of *Casuarina* and *Banksia* with the blackboy (*Xanthorrhoea*) and zamia (*Macrozamia Riedlei*). Jarrah is at its best on soils formed over laterite (Clarke, Prider, and Teichert, 1948, pp. 47–50) ; karri grows on soils directly "derived from the granitoid or gneissic rocks" (Gardner, 1944), which accounts for its occurrence on the lower country near the township of Denmark, and on isolated patches on the Porongorup Range and near Mt. Manypeaks. Gardner states that the karri forest contrasts strongly with the jarrah forest because of its larger trees, the karri and the tingles (*E. Jacksoni* and *E. Guilfoyli*), and because the undergrowth is denser and consists of broader-leafed trees and shrubs.

Gardner shows the eastern part of the strip as nearly all "sand-heath" (1944, Pl. X), which he describes as typical low heath with shrubs varying from 0.5 to 1 metre in height, though patches of taller shrubs and of small trees occur in many places (text fig. 22). There are small widely separated groups of the giant *Macrozamia Riedlei*, var. *Dyeri* between Esperance and Israelite Bay, both on the sand-heath and close to the sea, also the Western Australian Christmas-tree (*Nuytsia floribunda*) is common on the heath country, especially near Esperance. Shallow swampy depressions and small lakes (waterless for most of the year) are scattered over the heath ; in most of the swamps either paper-barks (*Melaleuca*) or Yate gums (*E. occidentalis*) are prominent ; in some places, near the coast, especially just east of Cape Arid, banksias are well represented.

The sand-heath passes northwards into either savannah or sclerophyllous woodlands (Gardner, 1944, pp. xliv–xlvi).

* The jarrah is *Eucalyptus marginata*, the karri is *Eucalyptus diversicolor*.

C. Soils

According to Teakle (1938) the Jarrah Region part of the Strip is in the major zone of grey, yellow, and red podsolized soils. The rest forms the Eyre Soil Region in the major soil zone of red-brown earths, passing northwards, in its western half, into the Stirling Soil Region of greyish, clayey soils, and, in its eastern half, into the Fitzgerald Soil Region, which is in the major soil zone of grey and brown solonized soils.

Mr. Robert Smith, Regional Officer, Division of Soils, C.S.I.R.O., has kindly allowed us to consult, and quote from, his paper, not yet published, on the physiography and soils of the Cranbrook-Mt. Barker Area, i.e., the western end of the Strip. He states that uplands of Pre-Cambrian rocks and the " ancient alluvial fill," in places 100 feet thick, of the wide, shallow valleys, are in the main covered by " a shallow mantle of Tertiary soils which have been but little disturbed by Quaternary rejuvenation of the rivers. Only in steep, narrow valleys of such streams as the Hay, Kalgan, and Frankland is the country rock sufficiently exposed for the formation of Quaternary soils." The Tertiary soils that have been formed on the uplands are generally either a lateritic gravel mixed with sand and underlain by several feet of kaolinized bed-rock or a grey, leached sand, about 2 ft. thick, overlying a few inches of pisolitic laterite which is underlain by kaolinized bedrock ; those formed over " ancient alluvial fill " consist usually of greyish sand in the clayey subsoil

Text Fig. 3.

Irregular and precipitous coastline in basic sill, West Cape Howe.
H. T. Phillipps, Photo.

of which there is an accumulation of one or more of the following :—sodium chloride, iron hydroxide, and calcium sulphate. The Quaternary soils are only in the narrow valleys of the rejuvenated streams and are shallow loams which vary according to the parent rock, into which they pass gradually.

The soils of the eastern three-quarters of the Strip belong, as already noted, to Teakle's Eyre Soil Region.

Reconnaissance soil-surveys by the Soils Division C.S.I.R.O. south of the Stirling Range have reached eastwards as far as the Pallinup River, and Mr. Robert Smith has kindly allowed us to make use of his unpublished report. We learn that the soils are predominantly grey and sandy, passing down in a few inches into a yellowish, more clayey sand with a layer of ferruginous "gravel," which, we suggest, is concretionary in origin. In many places this gravel is cemented into a continuous layer of laterite. At a depth of about 5 ft. the subsoil passes either into the spongolite of the Miocene Plantagenet Beds or into deeply weathered Pre-Cambrian rocks. In some parts of the area there are however fixed dunes, and in their deep sand, there is hardly any development of the sub-surface ferruginous material. In other places again solid laterite is exposed at the surface. In the valleys that have cut down about 200 ft. to the basement of Pre-Cambrian rocks, the soils do not have more a faint trace of the laterite layer. The observations recorded by Mr. Smith seem to us to show not only that the well-developed laterite layer, at or below the surface on the plain, was formed during a former physiographic cycle (Prescott, 1931, p. 49), but that, after the intervention of a more arid cycle, the present conditions again favour the formation of a ferruginous hardpan.

The soils of the "Esperance Plain" have been described (Teakle and Southern, 1937) as typically grey siliceous sands with a ferruginous or gravelly subsoil, replaced where the sand horizon is deep, by yellowish mottled clay with soft ferruginous gravel. In the few places where erosion has removed the 30 or more feet of incoherent material, the underlying gneiss is reached, which by weathering has produced a brown earth type of soil with woodland

Text Fig. 4.
Precipitous, gneissic cliffs, Point Hood, Doubtful Island Bay.
H. T. Phillipps, Photo

vegetation quite different from the heath of the plain. Near Scaddan, about 30 miles north of Esperance, mallee soils, which are greyish, calcareous, and solonized, make their appearance. They extend over large areas to the north of the Strip (Burvill & Teakle, 1938) and are quite distinct from the grey sands of the "Esperance Plain."

There does nor seem to be any published information about the soils between Esperance and the Pallinup River, nor about the soils east of Esperance.

The soil along the Israelite Bay-Norseman track is calcareous, with much travertine. This first appears at the top of the escarpment, about 10 miles north of the coast, and covers most of the country as far north as Mt. Ragged, where it is replaced by sandplain. This continues for some distance northwards, where travertine again occurs. Much of the country east of Mt. Ragged and the Russell Range is covered with travertine, which probably extends to the Nullarbor Plain.

The underlying rocks, wherever exposed, are the same metamorphic and igneous types as those to the west, where we did not find any development of travertine, and, in the vicinity of Mt. Ragged and the Russell Range, consist of quartzites and micaceous schists. It appears probable that the travertine has originated from calcareous dust, derived from the Nullarbor Plain during a more arid period.

This country carries very dense scrub. When Roe crossed it in November, 1848, he wrote that the "saplings" 12 or 15 feet high were "so densely packed that only axes could have opened a passage"; even the "scrubs of a more yielding character" were "frequently so dense that at a distance of three or four feet no part of a horse could be seen."

D. Coast.

1. *General.*—We have examined the 600 or so miles of coastline at fairly close intervals, except between Hopetoun and Esperance, confining our attention to the rocky parts, which have a total length considerably greater than have the intervening sandy beaches. If the rocks are fairly uniform both lithologically and structurally the coastline is smooth in plan and regular in profile, the reverse being the case where lithology or structure, or both, are varied. The neighbourhood of Point Hillier is an example of the first type; its cliffs rise almost vertically from near the shoreline to a height of 200 feet or more and form a nearly straight coastline for five miles. This and other stretches of uniform, rock-bound coastline in this part of the Strip are in Coastal Limestone, which is Pleistocene in age and is, in a broad sense, horizontally bedded, though, in detail, cross-bedded. Other less striking examples, formed in horizontal Miocene sandstones and shales of the Plantagenet Beds, were noted at Dillon Bay, and, running north for apparently about three miles, along the shore of Cheyne Bay.

Irregular, rocky coastlines are much commoner. They are carved out of metamorphic and igneous Pre-Cambrian rocks (text figs. 3–5). Jaggedness in plan large enough to show on a mile-to-the-inch map is mainly due to marine erosion acting along joints, but we have seen one impressive example due to a basic intrusion which is, owing to its structure, more susceptible to mechanical erosion than the surrounding rock; this is near Point Hood, where the waves have excavated a chasm about a chain wide and 200 feet deep along a basic dyke, and have, moreover, apparently tunnelled at sea-level along the dyke beyond the end of the chasm and then, as miners would say, have "risen"

about 200 feet to form a small "blowhole" several chains inland from the edge of the cliff. Again, at the cape on the south side of Duke of Orleans Bay there is a striking piece of coastal scenery, of which text fig 5 is a distant view. The contorted gneiss has strong joints trending N.N.W. and dipping east at 60°, and also has almost horizontal joints, but the jointing hardly explains the carving of the rock into several great rounded buttresses, and the presence on the south side of the biggest buttress of a corrie-like excavation facing the sea—though indeed one of its walls is a joint-face. Nowhere else along the coast have wee seen sculpturing like this, and closer examination may show, as it may also for the caves, etc., near Cape Le Grand which are described later, that the forms developed are due to unusual structures and other features in the gneiss.

Text Fig. 5.
Rounded buttresses of contorted gneiss, Duke of Orleans Bay.
H. T. Phillipps, Photo.

Text Fig. 6.
Wave-cut platform in folded quartzites and schists near the mouth of the Hamersley River.
H. T. Phillipps, Photo.

2. *Rock Platforms.*—Platforms, seldom awash in summer when we saw them, but doubtless wave-swept in winter storms, are noticeable wherever the Pre-Cambrian rocks are traversed by strong, nearly horizontal joints. In most places they are only a few yards wide, but there is a platform five chains or more across, in much folded quartzites and schists, near the mouth of the Hamersley River (text fig. 6), and the outer 15 chains of Point Malcolm (composed of gneiss) is a flat tongue within reach of storm waves.

Platforms in horizontally bedded calcareous sandstones, at, or a few feet above, sea level occur at Pt. Irby, Doubtful Island Bay, and east of the mouth of Hamersley Inlet and in many other places. At Pt. Irby the platform is about half-a-mile long and a chain or so wide (text fig. 7). A smaller platform of sandstone, lying on the " old rocks " occurs near the mouth of Hamersley Inlet. At the south end of Doubtful Island Bay, at the time of our visit, a sandstone breakwater about half-a-mile long, over which the waves were breaking, lay parallel to the shore, so that there was a strip of quiet water about a chain wide along the sandy beach.

Text Fig. 7.

Platform of cross-bedded sandstone, underlain by very coarse conglomerate, near Point Irby.

H. T. Phillipps, Photo.

Similar breakwaters occur parallel to Second, Third, Fourth and Eleven-mile Beaches, situated west of Dempster Head, and south of Esperance. The west end of the reef at Third Beach contains numerous waterworn pebbles of granite, evidently derived from the adjoining outcrop. The presence of these pebbles and fragments of recent shells suggests that the breakwaters are consolidated beach sand.

Dr. D. L. Serventy informs us that a similar breakwater, about three miles long, fringes the beach a little east of Hopetoun (fig 8) and is of considerable importance in connection with the salmon-fishing industry. Roe, on January 1, 1849, recorded the occurrence near " Flat " or " Smooth " Rocks, a few miles west of C. Knob, of a " ledge of flat rocks even with the water's edge, inside which was a sheltered space 20 to 60 yards wide and six to 10 feet deep." This was probably similar to the " breakwater " at Doubtful Island Bay.

These platforms and breakwaters of sandstone have probably been formed by the cementation of beach sands (Kuenen, 1950, p. 432). The precipitation of $CaCO_3$ in the sea, especially where it is broken by surf, has been explained by Fairbridge (1948, p. 26). Higher-level shelves, floored with metamorphic or igneous rocks and bordering on the coastline, were noticed in many places, *e.g.*, near Long Point, Cape Knob, and (from a considerable distance) on some of the islands. Much more impressive platforms, sloping towards the coastline at about 5°, and in places probably more than half-a-mile wide, occur about 250 feet above sea-level almost continuously for about ten miles on the sea side of Middle and East Barrens (fig. 9), and of West Mt. Barren. They are cut in metamorphic rocks and are trenched by small watercourses which drain the steep slopes of the hills. The gullies which we observed entered the sea at grade so that, where crossing the platform, they are 200 feet or more deep.

3. *Raised beaches and sea-built flats*—Flat areas a few feet above sea-level, of loose or slightly compacted sand, clay, and shells, in some places with considerable amounts of carbonaceous material, border parts of most inlets and occur in other places along the coastline.

A natural section of a raised beach, probably cut in Plantagenet Beds, occurs at the west end of Dillon Bay. The raised beach is about 10 feet above high-water mark and is covered with Coastal Limestone, slipped down from higher levels. A somewhat similar raised beach, pointed out to us by Mr. V. Serventy, occurs near the west end of West Beach (Esperance). It is about 10 feet above high-water mark, is from one to two feet in thickness, and is composed almost entirely of recent shells and shell fragments, including a number of *Patellas*, some of which still retain their original colour. Underlying it is aeolianite containing shells of the land-snail *Bothriembryon* a variety of which still lives on the sandhills above.

Text Fig. 8.

Sandstone "breakwater" fringing the coast a little east of Hopetoun.

D. L. Serventy, Photo.

The flat at the mouth of the Thomas River is only a few feet above high-water mark and carries a layer of marine shells in which *Anadara trapezia* is very abundant. At Cheyne Beach, 10 feet or perhaps more above high-water mark, Blatchford (1927) found quantities of shells similar to those in raised beaches near Perth.

A large flat about 20 feet above the sea lies between Point Malcolm and Israelite Bay and extends inland as much as five miles. In its S.W. part are claypans, bordered in many places by vertical banks, two or three feet high, of limestone largely composed of *Coxiella striatula.** This limestone also forms isolated "mushroom rocks" rising two or three feet above the surface of the claypan, on which *Anadara trapezia* and other marine shells are scattered. The greater part of the area is however a salt mudflat, at times covered with water and marked "Lagoon" on the maps. This lagoon is about five miles long from N.E. to S.W. The track from Point Malcolm to Israelite Bay skirts its S.E. side and is separated from the sea by a narrow belt of partly fixed dunes. In places near the track the flat is covered with many marine shells most prominent among which are* :—*Cardium racketti, Anadara trapezia, Ostrea sinuata, Katelysia scalarina,*— very abundant and very large specimens—*Cominella eburnea, Cominella lineolata, Niotha pyrrhus, Uber conicum, Parcanassa pauperata, Akera bicincta.*

Text Fig. 9.

Wave-cut platforms in metamorphic rocks, about 250 feet above sea level, on the south side of Middle Mount Barren Range.

H. T. Phillipps, Photo.

On the inland side of Point Dempster (Israelite Bay) waterworn boulders and pebbles of gneiss are scattered over flattened surfaces of the same rock, at heights varying from 40 to 60 feet above the sea.

Progradation is shown by :—Grassmere Valley (Jutson & Simpson, 1917, p. 56), a former strait between Princess Royal Harbour and Torbay Inlet, the tied island in Duke of Orleans Bay, at the mouth of Princess Royal

* Identifications very kindly made by Mr. B. C. Cotton (1951), Conchologist, The South Australian Museum, who notes in a paper now in the press that these shells are "remarkable in that they are frequently comparatively large, suggesting that conditions . . . . . were more congenial than those under which the same species live today. This stranded beach deposit is almost certainly contemporary with the well-known 15-20 ft. eustatic beach developed around the coast of Southern Australia."

Harbour, and according to local information, the tip of Point Dempster, which in the " early days " was separated from the mainland by a passage through which whaleboats could pass, but which is now filled with sand.

Miss Dirksey Cowan has kindly drawn our attention to another instance of progradation on the south coast, which certainly deserves mention, although it is far east of the part which we are describing. The schooner " Bunyip " was wrecked probably in 1876—at latest in 1878—near Twilight Cove, which is nearly 170 miles N.E. of Israelite Bay. In 1900 the hull was 200 yards inland and " separated (from the sea) by sandhills 8 ft. to 10 ft. high with saltbush."

4. *Caves.*—On the south side of Duke of Orleans Bay in a rather sheltered, north-facing position, is a wedge-shaped cavity 40 yards in length and 5 ft. high in front, its ceiling gradually sloping downwards to the floor for about 20 yards. Its floor is a joint in the gneiss which dips N.E. at 15° and is smooth and devoid of rubble, being within reach of storm waves. The roof shows shallow pits and very pronounced flaking, but has no " case-hardened " lip such as overhangs the entrance of some caves at higher levels which, although not coastal features, may be conveniently discussed here.

Frenchman Peak is an isolated hill of gneiss, 858 ft. high, which rises steeply for about 600 ft. above the surrounding plain country. The hill is pierced from north to south, about 100 ft. below the top, by a tunnel sloping down at about 10° to the south. The tunnel is about 50 yards long, 25 yards across at its north end, and widens to about 60 yards at its south end (text fig. 10). The roof, at its highest, is about 60 ft. above the floor, but curves down at the sides to 6 ft. or less ; its surface is smooth in a general sense, but in detail is very coarsely mamillate, and is dappled with dark and light patches. The dark patches are due to a thin skin, which was examined by Mr. G. G. Smith of the Department of Botany in the University of Western Australia, who tells us that it is formed by a microscopic alga. The white patches mark the places from which flakes of the dark-skinned rock have recently fallen. The floor is parallel to strong, S.E. dipping joints in the gneiss and is covered

Text Fig. 10.
Southern end of tunnel through Frenchman Peak.
H. T. Phillipps, Photo.

with dust and small fragments and flakes of gneiss—except near the north end, where it is strewn with large blocks of gneiss. On the west side is a platform, perhaps 2 or 3 ft. above the floor and several yards wide, along a joint parallel to the floor. There is no evidence of water-seepage in the tunnel, nor of its being frequented by any animals, and, although it must be a veritable funnel to catch the S.W. gales, the quantity of dust, etc., on the floor shows that the winds have little if any transporting effect. The tunnel is about the same height above the sea as the possibly wave-cut shelves on Mt. Ragged and the Russell Range, 80 miles to the E.N.E., which are mentioned later, but we did not notice any sign of wave-cut shelves on Frenchman Peak or the neighbouring hills.

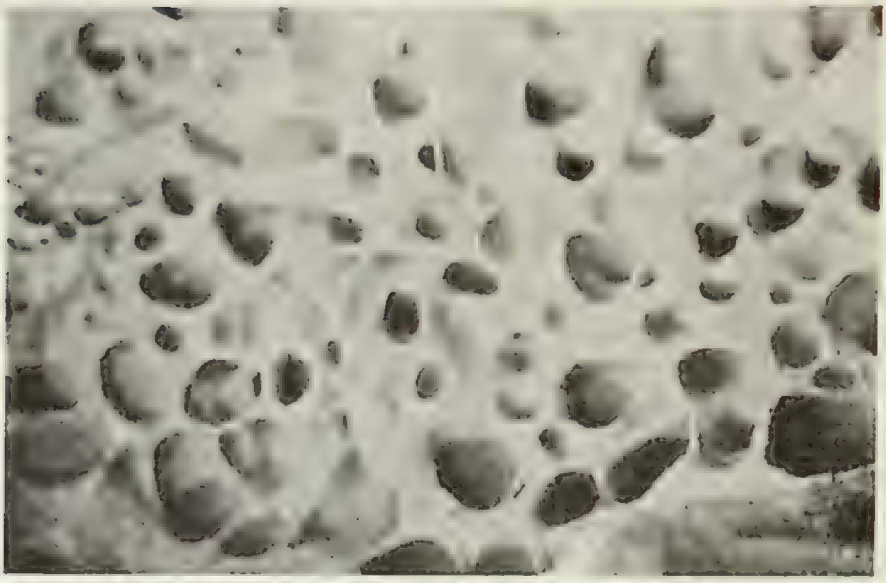
On the north side of Mt. Le Grand we examined three caves (text fig. 11) between 500 and 600 ft. above the sea, in gneiss, with varying jointing, etc. "No. 1" cave is about 20 ft. wide and deep and its front is overhung by a lip of "case-hardened" gneiss (Clarke, Prider & Teichert, 1948, p. 47). The front, 12 to 15 ft. high, is much protected from the wind by a thick growth of scrub. The back wall is pitted with holes nearly all more or less circular in cross-section (text fig. 12). They average about nine inches in diameter; their depth is not recorded but, from memory, it is about the same as their diameter; some are nearly two feet across, but the bottom of such a large hole is usually pitted with small ones. Every hole decreases in diameter inwards and is rounded at its base. The holes slope down towards the front of the cave. In the roof there are a few holes, shallower than those in the wall, but the outer part of the roof has none, and here alone is there much evidence of scaling. Unlike the Frenchman Peak tunnel, the Mt. Le Grand caves have no algal crust.

Text Fig. 11.

North side of Cape Le Grand, showing arched caves.

H. T. Phillipps, Photo.

"No. 2" cave is 55 yards across the front, 15 yards in greatest depth, and 30 feet in greatest height. Pitting on its back wall is much less regular and abundant than in "No. 1" but some of the pits are much larger and flaking is more evident. The gneiss appears to be less homogeneous than in "No. 1" and is irregularly seamed with pegmatite.



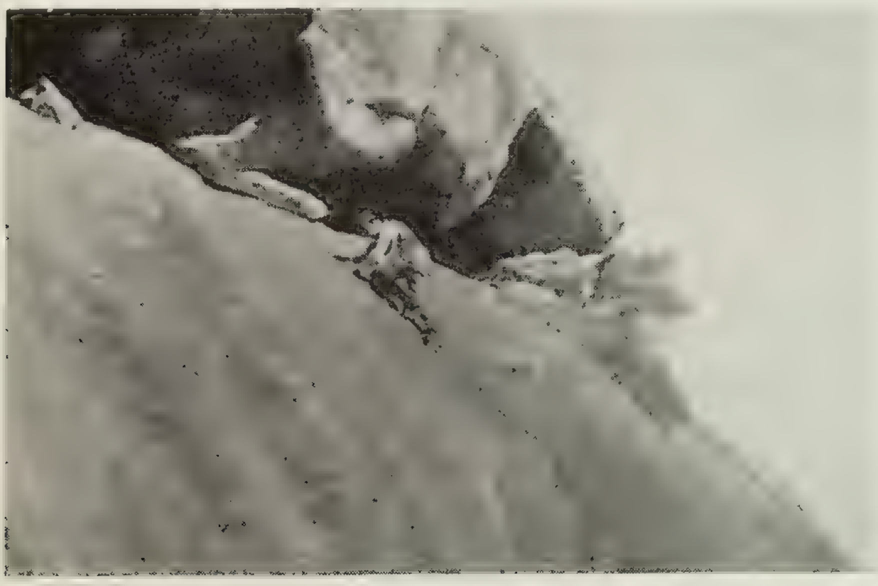
Text Fig. 12.
Pitted surface inside cave in gneiss, Cape Le Grand.
H. T. Phillipps, Photo.

"No. 3" is 145 yards across the front, is 20 to 30 yards deep and its maximum height is about 60 ft. (text fig. 13). The primary holes in the back wall are as much as 3 ft. in diameter and in depth, are irregular in cross-section, and enclose many secondary holes.

Text Fig. 13.
Cave No. 3 in gneiss, Cape Le Grand.
H. T. Phillipps, Photo.

The roofs of Nos. 2 and 3 were inaccessible. None of the three showed any evidence of wind action or of the presence of animals.

Some long, low caves, resembling that at the sea's edge in Duke of Orleans Bay, occur in a low cliff of gneiss near the house, about two miles north of the top of Mt. Le Grand. They are only 40 or 50 ft. above the sea, and separated from it by about three-quarters of a mile of swampy and sandy ground. Immediately behind the house the cliff faces S.E. and in it, about 30 ft. above the base, is a cavity, perhaps 50 yds. long, 10 yds. deep, and 10 ft. or less high (text fig. 14). The floor and roof are uneven, but, in parts of the roof there is widely spaced pitting, rather like that in the Cape Le Grand Caves, also there is the same overhanging (and incurved) lip. The cave follows joints which dip N.W. at about 20°. About 5 chains farther north the cliff swings to face S.W. and along this face there is a cave about 20 yds. long with a very pronounced overhanging lip. The roof is flaky and varies in height from 4 to 12 ft., the lower parts being in more quartzose phases of the gneiss. The cave seems to have formed along a joint and continues inwards, another 10 yds. or so, as a crack about 1 ft. wide along a parallel joint.



Text Fig. 14.

Cave in gneiss, about two miles north of Cape Le Grand, showing overhanging and incurved lip.

H. T. Phillipps, Photo.

Caves similar in shape to those in Mt. Le Grand occur on Dempster's Head (Esperance) and about a quarter of a mile west of Duke of Orleans Bay. Both these caves face west and are about 100 ft. above sea level. No pits were noted in their roofs and the gneiss appeared to have been removed in small flakes about 1½ inches in diameter and one-eighth in. thick. A somewhat similar concave type of weathering was seen in many large boulders of granite near Fourth Beach, Esperance.

No satisfactory explanation of the mode of origin of these caves has occurred to us, though some may no doubt be explained by the granular disintegration of the gneiss inside an indurated veneer, which has either been broken, or chemically destroyed by patches of vegetation, especially lichen

or moss, growing on the gneiss (White, 1944). Perhaps the four last described are due partly to marine corrosion, when sea-level was relatively about 80 ft. higher than now ; just as present-day wave action is partly responsible for the low-roofed cave at Duke of Orleans Bay. The Frenchman Peak tunnel may have been formed in the same way and record a time when sea-level was relatively several hundred feet higher. The high-arched caves on Mt. Le Grand may have originated quite independently of sea-action though it is noticeable that all those we have seen are at about the same level.

It was noticed that, on the side of Frenchman Peak, and also perhaps on Mt. Merivale (seen from a distance only) there is a tendency to the development of small, steep-sided recesses which might be likened to miniature cirques. These may possibly be the beginnings of caves of the high-arched type. Structure and lithology may play a part here, as suggested above for the corrie and buttresses near Duke of Orleans Bay.

5. *Beaches and Dunes.*—White sandy beaches form wide open bays between the rocky parts of the coastline. Behind them there is generally a belt of moving sandhills, which is seldom more than a few hundred yards wide, although in some places there are sand-drifts covering hundreds of acres, and steadily advancing inland. At the mouth of Dempster Inlet wind-driven sand thinly covers an uneven surface of schist and quartzite, and, from a distance, looks like a dune of rather unusual size and abruptness. The beaches rarely have exposures of the " old rocks " which were our main concern, and are tedious to traverse. We therefore avoided them, where possible, and have probably thus missed much information about raised beaches and progradation.

Dunes, fixed by scrub, and standing on ground at about the 20 ft. level, occur in many places along the coast, particularly between Point Malcolm and Israelite Bay, and near Esperance. Fixed dunes are also developed just inside the coastline at higher levels ; thus on the west side of Dillon Bay, near Cape Knob, the land rises very steeply from the coastline to 400 ft. or more, and is capped by fixed dunes, which overlie Coastal Limestone. Similar high ground a few miles west of Cape Knob carries fixed sandhills, which here also probably overlie Coastal Limestone. On West Cape Howe Promontory the metamorphic rocks north of a flat area underlain by a basic sill are, for some distance, covered by about a hundred feet of partly consolidated sand which seems to be interbedded with Coastal Limestone. This sand is fixed by heathy vegetation and is arranged in east-west ridges. The country N.W. to N.E. of Knapp Head has the same topography. Again, in similar surroundings just east of Point Nuyts, at heights of over 300 ft. above the sea, a similar terrain carries the small, permanent, freshwater Crystal Lake—the only one of its kind that we have seen in the Strip.

We unfortunately made no systematic notes on the character of the sands composing the beaches and dunes.

6. *Springs.*—These occur at many places along the coastline at contacts of Coastal Limestone or of unconsolidated sand with Pre-Cambrian rock. The largest that we have seen is on West Cape Howe Promontory, nearly a mile N.N.W. of the cape, close to the beach, at the contact between the fixed sand and the old rocks. At least four other large springs at similar contacts occur between Point Nuyts and the mouth of Nornalup Inlet. These are actively sapping back in the unconsolidated sand to produce very steep-sided

gullies, in one of which, heading near Crystal Lake and flowing north into Deep River, large karri trees grow, their leafy crowns rising above the brink of the gully, so that, from a little distance to the west, they look like a line of small trees growing on the undulating moor.

7. *Inlets.*—" Inlet " appears often on maps of the south cost of Western Australia but has hardly the meaning of a " small arm of the sea," just as the many " lakes " in the interior of the State are not lakes in the generally accepted sense. There are about twenty " inlets," large and small, in the Strip. One, Waychinicup, is completely rockbound, except for a narrow opening ; the rest are partly or completely closed by sand-bars, which have driven the actual or potential mouth eastwards in some, westwards in others, but at the Gordon Inlet, at the mouth of the Gairdner River, appear to have closed the mouth from both directions. These differences are doubtless due to local currents, mentioned in a previous section.

Only four inlets can be said to be " permanently " open to the sea ; of the rest, some are known to have been open at times in the last hundred years, of others there is no record. On a map the inlets have the outline of drowned valleys, but, so far as we know, they are flat-floored, the slopes of the surrounding hills not being continued under the water which covers some of them. We have already, in discussing the sea floor, noted that the King-Kalgan Inlet (Oyster Harbour) is the only one from which a continuation across the continental shelf has been traced—though other submerged channels may be detected when many more soundings are available. A few inlets are always covered with water ; most are boggy flats with a crust of " salt " (mainly sodium chloride) (text figs. 2, 15), but having in places a very shallow sheet, or just a film, of very saline water. No defined channel across any of these flats is noticeable. In March, 1949, Mr. H. A. Ellis (Government Geologist), pointed out that there was then a constant strong " spring " of sea-water at the foot of the dune which separates Culham Inlet from the ocean, so that, at that time, the surface of the inlet was below sea-level ; on the other hand,

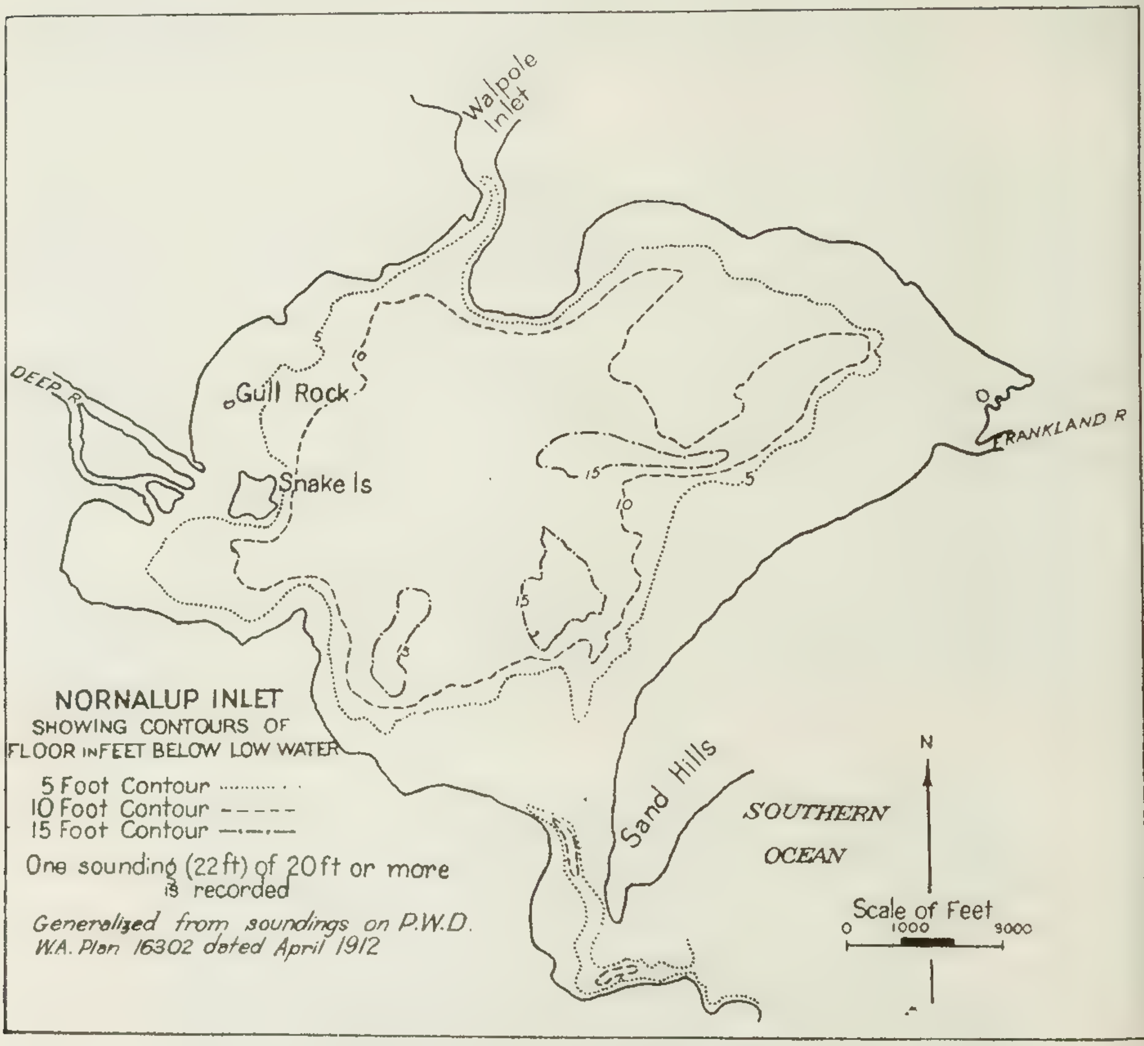
Text Fig. 15.

Middle Mount Barren and Dempster's Inlet.

H. T. Phillipps, Photo.

a century before, in April, 1849, A. C. Gregory recorded that after heavy rains the water in Culham Inlet had risen 7 ft. above its "usual level" when it broke through the bar, and for three days the outflow was too strong for his horses to cross the mouth by swimming.

The only complete information as to the floor of a permanently water-covered inlet is given by a detailed plan of the soundings in Nornalup, which was made nearly 40 years ago and from which, by kind permission of the Under Secretary of the Public Works Department, we have compiled text fig. 16. This shows that the floor of the inlet is almost as flat as that of an inlet now reduced to a mud flat.



Text Fig. 16.

Nornalup Inlet.

A little information about the floor of Wilson Inlet is given by a plan of soundings, made in 1919, near the mouth of the Denmark River. The inlet is 6 ft. deep or more where the river enters it, but at 100 ft. out from the river mouth the water shoals to 2 ft. or less, and this shallow water persists for 1,200 ft. in a S.E. direction. Beyond that no soundings are shown but it is noted that the water "deepens towards the ocean bar."

Material brought in by occasional floods and by wind has probably obliterated the channels both on the water-covered and on the mud-covered inlets.

Waychinicup (text fig. 17), on the east side of Mt. Manypeak, is the only inlet without a sand-bar that we have seen on this coast. It is at the end of a rather wide, rocky valley through which flows a perennial stream. Capt. Pedersen and Mr. N. E. Stewart of the C.S.I.R.O. Fisheries Research Vessel "Warreen," have, through Dr. D. L. Serventy, very kindly supplied the following particulars regarding this inlet: It has a steep-sided entrance, about 80 yards wide, without a bar, and is an excellent harbour for boats up to 40 feet long, although, with an onshore wind or unusually heavy swell, there would be broken or confused seas in the entrance owing to its narrowness. Just inside the entrance the inlet turns sharply to the east and is completely protected from every quarter. The inner part is only deep enough for rowing boats (having been no doubt silted up by the creek) but the outer part is fully 12 feet deep and measures about 300 by 300 yards.

Text Fig. 17.

Waychinicup Inlet.

H. T. Phillipps, Photo.

There appear to be but few inlets between Hopetoun and Esperence—a part of the coast that we have not seen—but, judging from the map, there are many coastal lakes, such as Jerdacuttup and Shaster, which are near, but perhaps not connected with river mouths. Possibly field-work will show that these lakes were once part of inlets at the mouths of the rivers and have been cut off by drifting sand. The relative absence of inlets in the eastern part of the Strip would thus be due to the weakness of the rivers; however, such coastal lakes as the "salt lagoon" at Israelite Bay, and Grassmere, about 10 miles west of Albany (Jutson & Simpson, 1917, pp. 56, 58) were probably formed by progradation.

E. Hinterland.

1. *General.*—The part of the Strip that lies west of a line running about north from Albany differs from the rest, as already noticed, in vegetation and soils: the two parts differ also topographically.

Mr. Robert Smith, to whose work on the soils we have already referred, has kindly allowed us to make use of his unpublished account of the physiography of the western end of the Strip, and of the eastern part as far as the Pallinup River. We hope that we have not mis-represented Mr. Smith's views in combining our observations with his.

2. *Jarrah Region Part.*—This is an undulating, forested plateau which rises above 1,000 feet only in isolated hills, such as Mt. Lindesay and Warriup Hill.* This type of country persists southwards to within 10 miles or less of the coastline, which has already been discussed. In some places indeed the hilly country, only exceptionally rising above 500 feet, extends to the coastline, but the coastal fringe of high land is in most places separated from the hinterland by a low-lying strip of swampy or sandy ground, *e.g.*, between Torbay Inlet and Princess Royal Harbour (Clarke, Prider, and Teichert, 1948, pp. 112–3) and near Long Point (text fig. 18).

Text Fig. 18.

Swampy coastal country east of Warriup Station.

J. Clarke, Photo.

The plateau averages 800 to 900 feet above sea-level. The valleys, which cross it, vary from juvenile to senile. The Frankland, Deep, Hay, Denmark, and Kalgan Rivers are juvenile, and the last three are cutting back into the senile Upper Kent River. The Kent is juvenile in its lower, southern part, senile in its upper, northern part, where it is more or less connected with a series of shallow lakes and swamps, of which Lake Matilda is one, trending east and west. There is a similar east-west-trending series of lakes and swamps in the vicinity of Lake Muir. The Gordon, which joins the upper Frankland, is a senile east-west river.

There are thus, in this part, valleys of two types—an older east-west system and a younger north-south. The older is now a belt, 30 miles or so wide, of almost level country on which are many swamps and shallow lakes. It drains westward from near the Perth-Albany railway line, at least as far as

* There are two hills called "Warriup" in the Strip—that mentioned here is about 8 miles west of Cranbrook, the other is near the coast, about 43 miles N.E. of Albany.

Lake Muir, and is crossed by the juvenile Frankland, and partly crossed by the Deep, whose head is cutting back towards Lake Muir. Drainage along this belt has been partly blocked, during a former more arid cycle, by wind-blown material, thus leading to the formation of swamps and lakes, many of which are connected at times. It is noticeable that soluble salts are more concentrated in the lower, western, parts of the system so that freshwater swamps may occur on the higher ground, brackish or salt-water on the lower.

Here then are the same two types of valley as near the west coast, east of the Darling Scarp (Jutson, 1934, p. 171) but there the north-south valleys are the older, and here there is no structure comparable to the Darling Scarp.

3. *Stirling Region Part.* This, broadly speaking, is a plain, between 200 and 700 feet above sea-level, above which stand many isolated hills. Near Ravensthorpe, however, a belt* about 30 miles wide, of greenstone country crosses this plain and reaches within about 25 miles of the coast. Woodward (1909 (b), pp. 7 9) writes that this belt is dominated by the Ravensthorpe Range, which runs N.W. from Kundip, and is more conspicuous from the lower country to the S.W. than from the N.E. " where the adjoining plains are more elevated." In detail, as described by Woodward and illustrated by H.W.B. Talbot's contour map in the same bulletin, the topography of the Ravensthorpe belt resembles that of the " greenstone belts " of the Kalgoorlie Region to the north, and is quite unlike that of the Stirling Region, and will not be further discussed here.

Text Fig. 19.

Mount Ragged from the north.

H. T. Phillipps, Photo.

(a) Plain.—The plain, but for the interruption of the Ravensthorpe belt, stretches from near the Perth-Albany railway to Cape Arid. It is, quite apart from the many valleys which cross it, not all at one level as the word " plain " might imply, and what little evidence there is indicates that it slopes down very gently to the south. There is also some indication that, coming south, there is a break of some abruptness between the 400 and the 200 feet levels, but this is largely only an " impression " supported to some extent by aneroid readings.

* Part of the Kalgoorlie Region, the boundaries of which as shown by Clarke (1936, p. xii.) needs much alteration.

The only accurate levelling across the Strip (*i.e.*, from north to south) is along the Perth-Albany, Ravensthorpe-Hopetoun, and Coolgardie-Esperance railways. The country near the Perth-Albany line is dotted with isolated hills, and slopes down very gently (at less than 1 in 400) southwards till within 10 miles of the sea, where the slope steepens to about 1 in 95, until it reaches the narrow plain, about 20 feet above the sea, which, as already noted, lies behind the coastal hills in many places in this part of the Strip. The country bordering the Coolgardie-Esperance line has a similar profile, but the low-level plain is largely obscured by fixed sandhills.

The northern part of the Ravensthorpe-Hopetoun railway passes along a belt that is, as already noted, quite different from the "plain," but the southernmost 10 miles or so is over a scrub-covered plain about 100 feet above the sea.

Text Fig. 20.

Platform on Mt. Ragged, with large rock which has probably rolled down from steep upper slope.

H. T. Phillipps, Photo.

The Israelite Bay-Norseman track crosses plain country above which rise many hills, of which Mt. Ragged (1920 feet) is the highest (text figs. 19–20). Mt. Ragged is a hogback completely surrounded by a platform from 200 to 500 yards wide along the sides of the mountain, the width increasing to about 60 chains at the north end. The platform slopes outwards at about 5° and is almost unbroken by gullies at the south and east sides of the mountain. At the north end, the platform is cut by two deep gullies, and, although it is broken by numerous gullies on the west side, its identity is very apparent when it is viewed from a distance. An even better-defined platform occurs, at the same height, round the Russell Range four miles to the north (text fig. 21), possessing similar characteristics to that on Mt. Ragged. The platforms on both Mt. Ragged and the Russell Range are cut through the highly inclined quartzites and schists, of which both are composed, and resemble the platforms on the coast between Middle and East Mt. Barren, which are however only about 250 feet. above the sea. Similar shelves, apparently at the 800 feet level, are visible from Mt. Ragged on other hills

to the east and west. We saw no waterworn pebbles or boulders on any of these shelves, but nevertheless it seems highly probably that they record former sea-levels. The Mt. Ragged and Russell Range shelves were possibly cut during the Miocene submergence (Clarke, Teichert, and McWhae, 1948, p. 98).

Text Fig. 21.
Probable wave-cut platform, Russell Range, at 800 foot level.
H. T. Phillipps, Photo.

Aneroid readings along the Norseman-Israelite Bay track show that here also the plain, which near Mt. Ragged, is about 500 feet above the sea, slopes southwards very gradually, until, seven miles from Israelite Bay where it is about 300 feet above the sea, it gives place to a slope of about 1 in 40, which leads down to the fixed-dune country on the N.W. side of the coastal lagoon already mentioned. A few miles east of this track there is no escarpment and the plain slopes gradually from about Mt. Ragged to the level of the coastal lagoon.

The track running westwards towards Esperance, north of C. Pasley, is over plain country, largely heath-covered, with many scattered hills, the plain being by aneroid 200 to 300 feet above the sea. Between the Pallinup R. and Green Range there is an approximately level surface 400 to 500 feet above the sea, whereas the plain country S.W. of Green Range and reaching nearly to Cheyne Beach, is on the average not more than 200 feet high. From Ongerup southwards to a line running about east from near Graves Hill, the general level is between 500 and 800 feet and the country gives the impression of being a somewhat dissected plain, but south of this there is a pronounced fall to the 200 to 300 feet level. The very mild scarp separating these two plains is visible for some distance trending east. The 200 to 300 feet plain (text fig. 23) seems to persist eastwards interrupted by valleys, to the Fitzgerald R., as far up as about 10 miles from the sea. A belt of level country, of about the same elevation (text fig. 22) separates the Middle Mt. Barren and Eyre Ranges from higher ground to the north, which is crossed by the road to Ravensthorpe, and which appears to be a continuation of the 500–800 foot plain near the Pallinup River. The Ravensthorpe-Esperance road,

once it has crossed the Ravensthorpe belt, lies over the plain. East of the Oldfield R. this plain is below the 200–300 foot level, which however, may well be present to the north of the road—country over which we have not travelled. The Esperance-Israelite Bay track is generally at the 200–300 foot level, which extends to the sea as far as Cape Pasley. Beyond this the track descends to the low-level (20 foot) plain, as already described.

Text Fig. 22.

Typical low heath country north of Middle Mount Barren Range.
H. T. Phillipps, Photo.

(b) Rivers.—Ten or more major "rivers" cross the eastern portion of the Strip. Their direction is in the main south-east, unlike those of the western part, which, in a general way, flow from north to south. There does not seem to be any trace of a senile east-west river system, such as Mr. Robert Smith has found in the western part. The drainage channels of this eastern portion carry running water more rarely than those of the western—a result, partly of the smaller rainfall, partly of the presence in the lower reaches of many of the streams of a considerable thickness of absorbent Plantagenet Beds, overlying the generally impervious Pre-Cambrian rocks; in most of them however pools of brackish or salt water are common. As we move eastwards from the Perth-Albany railway the watercourses become progressively shorter: thus the Kalgan and Pallinup Rivers head as far inland as many of those in the western part, the heads of the Gairdner, Fitzgerald, and others, as far east as Esperance, are apparently only a little way beyond the north edge of our map, except the Lort, which "extends far into the interior, draining the salt lakes of the Dundas Hills" (Woodward, 1894, p. 15); east of Esperance few drainage channels seem to persist as much as 10 miles north of the coastline, though shallow continuations may exist in the almost unmapped country farther north.

Where the valleys are in the horizontal Plantagenet Beds or (as in the middle part of the Fitzgerald) in a soft schistose phase of the Pre-Cambrian, the stream meanders over flats, seldom a mile wide, abutting against cliffs (text fig. 23); where the valleys are entirely in hard Pre-Cambrian rocks the sides slope rather gently down to the watercourse.

Text Fig. 23.

Cliffs of Plantagenet Beds on west side of Fitzgerald River, Fitzgerald Inlet in background.

H. T. Phillipps, Photo.

The river beds, wherever we have seen them, seem to have arrived at the base-level of erosion, and this characteristic is maintained where some of the rivers in the lower part of their course pass through steep-sided gorges, as for example the Phillips in its gorge through the eastern end of the Eyre Range, and the short St. Mary River (near Point Ann), and Willyun Creek (a little west of Cape Riche). Even the short gullies, that run S.E. off the Middle and East Barrens, have cut very deeply into the 250 foot platform that fronts the range.

A stream, probably a tributary of the Lort, crossed by the Ravensthorpe-Esperance road about 10 miles east of the Lort, is rather unusual in that it is at a different stage of development from the mature valleys of the neighbouring Lort and Dalyup. It lies in a trench, six feet deep, in the plain, which is about 200 feet above the sea, and has every appearance of being a very young, consequent stream, which has just begun to incise the plain.

(c) Lakes and Swamps.—The plains of the eastern part of the Strip are dotted with many small, shallow, unconnected lakes and swamps, some of which are shown on our map. Most of them are dry in summer, and in many the water is salt or brackish, but in a few, of which Pabelup, about six miles north of Mt. Bland, is an example, there is nearly always useful water. Swamps and lakes on the plain are particularly numerous between Esperance and Israelite Bay and are a serious hindrance to travel in wet weather. In the Kalgan-Pallinup district they are, Mr. Robert Smith suggests, possibly due to the removal in solution of calcareous matter from very fossiliferous patches in the underlying Plantagenet Beds. Supporting this suggestion, we noticed, near Warriup Homestead, about 39 miles N.E. of Albany, where the Plantagenet Beds are rather richly fossilferous, that there are several small crater-like hollows, which seem to be of the nature of swallow-holes. However, some of the lakes and swamps cannot be thus explained. For example, about seven miles north of Pine Hill, close to the Israelite Bay-Norseman track, is a circular salt-pan about five chains across, surrounded by a

Text Fig. 24.

Photo of east end of Stirling Range from the south.

H. T. Phillipps, Photo.

granite " cliff " about six feet high ; again, about seven miles S.E. of Howick Hill, on the Esperance-Israelite Bay track, is a completely enclosed bare surface of gneiss, about one chain across and two feet below the general level. We cannot suggest how these features originate.

(d) Water Supply.—There are many lakes, swamps, and rivers, nearly all salt or brackish, in the Stirling Region part of the Strip, and we have seen a map on which quite a number of " springs," etc., are shown. Actually, supplies of potable water are very small and scarce, except after rain, which quickly makes much of the country boggy and difficult to cross.

(e) Hills.—These have been mentioned in earlier parts of the paper, but attention might be drawn to the difference between the hills (Mt. Ragged, Russell Range, and others) at the east end of the Strip, and those farther west (Sirling Range, the Barrens, and Eyre Range) ; the western group have not the 700 800 foot shelf, which is a striking feature of the easternmost hills (text fig. 21). There is, indeed, a shelf on the Barrens (text fig. 9) but it is about 250 feet above the sea and is only on the south side. We have not noticed, nor does Woolnough (1920) record, any feature of this kind in the Stirling Range (fig. 24).

IV. CONCLUSION.

The area discussed consists of two rather distinct parts—a western, which probably continues to Cape Leeuwin, and an eastern, which gives place to the Nullarbor Region, not far east of Israelite Bay.

The western part is a dissected plateau of Pre-cambrian rocks, drained by south-flowing, rather young rivers, but having also the remains of an older east-west drainage. The adjacent sea-floor, at about 20 miles south of the coastline, slopes steeply to 1,000 fathoms or more, and the continental shelf carries but few islands.

The eastern part is, on the average, distinctly lower than the western. It is essentially a plain in which there are two or more steps, and above which many island-like hills of Pre-Cambrian rocks rise to various heights. Some of the hills were islands, others were submerged rocks in the Miocene sea, which covered the land to a depth of at least 900 feet, as evidenced by the Miocene rocks at Norseman, 100 miles north of Esperance.

The sea-floor off the eastern part is extremely irregular, and is studded with islands for 30 miles or so to the south ; beyond which it probably plunges steeply, as in the western part ; the various heights of the protrusions of Pre-Cambrian bed-rock through the Miocene some barely uncovered, others still buried, show that the bed of the Miocene sea was also very uneven.

Coastal Limestone does not, so far as we know, occur on the mainland east of long. 120 E. but is reported from some of the islands of the Recherche Archipelago. This suggests that the coastline of the eastern part of the strip has retreated after the formation of the Coastal Limestone, whereas the western part has remained stable. The retreat of the eastern part, if verified, is most plausibly ascribed to earth movements, which did not occur in the western part.

Platforms, at heights ranging from 800 to 200 feet and less above present sea-level, indicate, as do the steps on the plain, that there were several pauses in the emergence of the present land surface. Apparently such shelves are not recognizable in the Stirling and Porongorup Ranges, or in the western

dissected plateau ; this suggests that some large dislocations separate the western part from the eastern,—in which connection Woolnough's horst theory of the origin of the Stirling Range should be noted.

Fixed sand dunes at various heights, some 200 feet or more above sea-level, and the wide distribution of a cuirass of laterite or duricrust, indicate that the present cycle was preceded by a more arid one, during which, perhaps, the marginal deposits of calcareous sandstone, now compacted into Coastal Limestone, were formed. Sea-built accumulations of sand, etc., at, or close to, present sea-level, and the fact that all valleys are at grade along the coast-line, show that the present cycle has long been in existence.

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PART OF THE SOUTH COAST OF WESTERN AUSTRALIA
SHOWING THE FEATURES MENTIONED IN THE TEXT
317 Heights (in feet) from maps by Dept. of Lands and Surveys, from W.A. Govt. Railways and from 'Australia Pilot' Vol. I, 2nd Edition 1927
2667 Soundings (in fathoms) from Admiralty Chart 2759b corrected to 14 Dec. 1946
Railways
Roads
Tracks
Hills
Ranges
Swamps and Lakes
Old Telegraph Line
LOCALITY MAP
MILES
NORTH WEST CAPE
PERTH
C. LEEUWIN
ALBANY
ESPERANCE
ISRAELITE B.
SALMON GUMS
GRASS PATCH
SCADDAN
GIBSON
RAVENSTHORPE
KUNDIP
OLDFIELD R.
YOUNG R.
LORT R.
DALYUP R.
PHILLIPS R.
ESPERANCE
PINK L.
HOWICK H.
MT MERIVALE
MT RAGGED
ISRAELITE B.
CHRISTMAS I.
DUKE OF ORLEANS B.
FRENCHMAN PK.
CAPE LE GRAND
MONDRAIN I.
WEST GROUP
WEST I.
L. SHASTER
HOPETOUN
L. JERDACUTTUP
CULHAM IN.
EYRE R.
E. MT BARREN
MIDDLE MT BARREN
HAMERSLEY R.
FITZGERALD R.
DEMPSTER IN.
MT BLAND
W. MT BARREN
DOUBTFUL IS BAY
Pt. Hood
BREMER B.
C. Knob
FLAT ROCK
Pt. Irby
CHEYNE B.
C. Riche
HAUL-OFF ROCK
Cheyne Beach
WARRIUP H.
GREEN RA.
BALD I.
MT MANYPEAK
OYSTER HARB.
KING GEORGE SOUND
Bald Head
PRINCESS ROYAL HARBOUR
ALBANY
Torbay Hd.
West Cape Howe
Knapp Hd.
Pt. Hillier
Pt. Irwin
Pt. Nuyts
Long Pt.
CHATHAM I.
NORNALUP INLET
BROKE INLET
DEEP R.
MT FRANKLAND
KENT R.
DENMARK
DENMARK R.
MT LINDESAY
WILSON INLET
MT BARKER
PORONGORUP RANGE
KALGAN R.
STIRLING RANGE
BEAUFORT INLET
PALLINUP R.
GRAVES
GAIRDNER R.
JARRAMONGUP
GNOWANGERUP
ONGERUP
BORDEN
TAMBELLUP
GORDON R.
CRANBROOK
WARRIUP H.
TENTERDEN
L. MATILDA
L. MUIR
TONE R.
FRANKLAND R.
ARCHIPELAGO OF THE RECHERCHE
TWIN ROCKS
TERMINATION I.
100 fathoms

4.—AN EXAMINATION OF CLAYS FROM MARCHAGEE AND CARDABIA, W.A.

by

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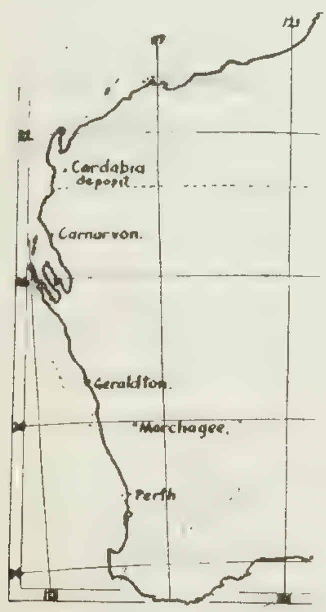
ABSTRACT.

The mineralogical composition of three samples of clay was determined by comparing the results of an X-ray analysis (by the Debye Scherrer powder diffraction method) with those of a chemical analysis. Two clay samples from Marchagee were shown to consist almost entirely (apart from non-clay minerals) of a montmorillonite-type clay (saponite), while a sample from Cardabia contained a mixture of the montmorillonoid, kaolin and mica types.

OCCURRENCE.

The samples were collected from Cardabia and Marchagee (*see* text fig. 1) by Sofoulis (1) and Glance (2) of the Geological Survey. The beds at Cardabia formed part of a Cretaceous sequence, and were exposed by erosion of the crest of a broad anticline. The "bentonite"* layer bottoms on Radiolarian siltstone, and is overlain by *Inoceramus* marl and limestone. Its thickness has been estimated at about 10 ft., and the area of the deposit is about 38 sq. miles.



The bentonite at Marchagee has been commercially worked for some years. It is of recent formation, and occurs in the form of claypans in the bed of a larger lake depression, which is limestone of possibly Cretaceous age. The total area covered by the bentonitic clay-pans amounts to about 1/8 sq. mile. On the particular mineral claim from which our samples were taken (M.C. 397H), there is the following downward sequence :—

1. Top bentonite layer, about 10 in. thich (Top Layer.)
2. Gypseous clay about 11 in. thick.
3. Lower bentonite layer, about 13 in. thick (Bottom Layer).
4. White limey sand.

ANALYSIS.

The cylindrical diffraction camera described by Shearer (3) was of radius $2 \cdot 865$ cms., with slit of dimensions $0 \cdot 4 \times 2 \cdot 5$ mm., and line spacings on the film were estimated visually to $0 \cdot 1$ mm. The camera recorded spacings between about $1 \cdot 3$A and 20A, using cobalt K radiation.

* Local clays, rich in montmorillonite, are referred to in References (1) and (2) as bentonites. This term will be hereafter retained.

All specimens examined comprised clay material as collected. Two methods of mounting were used. In one, a slot slightly smaller in cross section than the collimating slit was cut in celluloid 0·2 mm. thick. Into this slot the powder was packed. In the second method of mounting, yielding higher sensitivity in analysis, the aggregate technique described by Nagelschmidt (4) was employed. A flake of ordered aggregate material was mounted in front of the slit parallel to the X-ray beam. In some cases, this type of specimen was treated with glycerol, in order to obtain a montmorillonoid complex with a stable basal spacing (5). This valuable technique removes the uncertainty caused by the variation of the basal spacings of montmorillonoids with their degree of hydration. The camera was calibrated for powder specimens, using the known spacings of KCl and borax, and a correction curve drawn. The same calibration was observed to hold for the second method of mounting.

The observed d/n for basal spacings, using unfiltered radiation, was too high ; but after making exposures using an iron filter, it was concluded that at these small Bragg angles, the α and β lines were unresolved, resulting in an effective increase of the spacing.

The values of d/n were identified using a recent publication on clay minerals by the Mineralogical Society (6) and also the revised A.S.T.M. card index (7) ; the approximate composition was then estimated by visual observation of the line intensities on the photographs.

Auxilliary tests made to confirm the analysis included heat-treatment of the montmorillonite and kaolin-type clays.

The observed spacings and their identification are given in Tables 1 and 2, where the composition arrived at by X-ray methods alone is compared with the figure subsequently obtained by employing the chemical analyses also.

TABLE 1.

Marchagee Bentonite—(Glycerol Treated).

Top Layer.			Bottom Layer		
Intensity	d/n (A).	Identification.	Intensity	d/n (A).	Identification.
VS	18.	Mo	VS	18.	Mo
VW	12.	Se	VW	12.	Se
M	9.1	Mo	M	9.0	Mo
VW	5.9	Mo	VW	6.1	Mo
M	4.52	Mo + Se			
W	4.25	Q			
W	3.54	Mo	M-W	3.53	Mo
M	3.34	Q	M-W	3.35	Q
S	3.03	Cal	M	3.03	Cal
			W	2.92	Mo
M	{ 2.60	Mo + Se	M-W	2.58 }	Mo,Se
	2.48	Se	W	2.49 }	Se
M	2.28	Cal + Se	W	2.28	Cal,Se
			VVW	2.20	
M — W	2.09	Cal + Se	W	2.10	Cal,Se
W	1.92	Cal			
M — W	1.87	Cal	VW	1.88	Cal
W	1.68 ± 0.2	Mo	VVW	1.60	
S	1.53	Mo, Q	M	1.53	Mo, Q
VW	1.46		W	1.32	Mo
VW	1.38	Q			
VW	1.32	Mo			

Abbreviations : Mo = Montmorillonite ; Q = Quartz ; Se = Sepiolite ; Cal = Calcite.

Approximate Percentage Composition.

From X-ray Data.		From X-ray data and chemical analysis.	
Trioctahedral Mo Clay	75	Saponite	75
Calcite	15	Calcite	8
Quartz	10	Free Silica	11
Sepiolite	Trace	Sepiolite	3
(There may be slightly more sepiolite in Bottom Layer than in Top Layer.)		(Salts and Oxides	3)

TABLE 2.

Cardabia Bentonite.

Intensity	d/n (A).	Identification.
VS	15.9	Mo
W	10.1	Mica Clay
W	8.9	?
VW	7.9	Mo or Kaβ
S	7.15	Ka
W	4.46	Mo, Mica
W	4.24	Q
W	3.96	Kaβ
VVW	3.70	Qβ
M	3.57	Ka
M–S	3.34	Q, Mica
W	3.16	Mica?
W	2.98	Mica
VW	2.80	Mica
M–W	2.57	Mica, Mo, Ka
VW	2.46	Ka, Mica?
VW	2.38	Ka
W	2.13	Mica
W	2.00	Mica
W	1.81	Q
W	1.66	Ka, Mica
VW	1.54	Ka, Q.
W	1.50	Ka, Mo, Mica
W	1.38	Q
VVW	1.30	Mica

Abbreviations ; Mo = Montmorillonite ; Ka = Kaolinite ; Q = Quartz.

Approximate Percentage Composition.

From X-ray Data.		From X-ray data and chemical analysis.	
Dioctahedral Mo Clay	40	Nontronite	40
Kaolinite	30	Kaolinite	25
Mica Clay	20	Mica (Muscovite or illite)	20
Quartz	10	Free Silica	15

Chemical analyses were carried out by D. Burns, Mineralogical Chemist and Research Officer in the Government Chemical Laboratories. These confirmed the X-ray analyses, and allowed more definite conclusions to be made as to the proportions and type of minerals present.

In the case of the Marchagee sample, two chemical analyses were made—one on portion of the material used in X-ray analyses, and one on the finest fraction ($> 2\mu$) after removal of silt. It is to be expected that the percentage of those elements associated with the clay mineral itself will be increased in this "clay fraction," whereas the percentage of those associated with non-clay minerals, which are normally of relatively large grain-size, will be reduced. From these analyses an estimation of the free silica was made, by comparison of the magnesia—silica ratios, and the nature of the montmorillonoid clay was more reliably checked. "Free silica" could include the silica content of any non-clay silicates such as felspars, etc.

Table 3 compares the percentages by weight in the aggregate (from the chemical analyses) with those of a hypothetical specimen composed of the sum of the minerals found from the X-ray data. The compositions are typical of the various minerals, and are obtained either from the formula or from actual chemical analyses as appearing in (6) or (7). The percentages in which the minerals are combined have been adjusted to give best agreement with the chemical analyses.

The percentages of silica and calcite were fixed by comparing the two chemical analyses (the X-ray evidence suggested a considerably higher figure for calcite), a trace of sepiolite was added, and most of the remainder was attributed to saponite, a trioctahedral montmorillonoid clay rich in magnesium. There were also chemical traces of salts, oxides and silicates in too small proportions to give an X-ray pattern.

TABLE 3.

Marchagee Bentonite (Top Layer).

—	8 per cent. Calcite.	11 per cent. Free Silica.	3 per cent. Sepiolite.	75 per cent. Saponite.	Total.	Chemical Analysis. Aggregate.	Chemical Analysis. Silt-Free.
SiO_2	....	11.0	1.5	34.0	46.5	46.80	41.79
Al_2O_3	....	....	....	5.0	5.0	5.01	5.35
Fe_2O_3	....	....	0.1	2.5	2.6	2.62	2.96
FeO	....	....	....	....	....	0.54	0.16
MgO	....	....	0.6	17.6	18.2	18.19	21.12
CaO	4.5	....	....	....	4.5	5.15	4.84
H_2O+	....	....	0.6	15.0	15.6	6.33	6.61
H_2O-						9.03	12.60
CO_2	3.5	....	....	....	3.5	3.97	3.19
MnO	....	....	....	....	....	0.08	0.08
K_2O	....	....	....	....	....	0.28	0.28
Na_2O	....	....	....	....	....	1.34	0.52
TiO_2	....	....	....	....	....	0.29	0.28
C (Humus)....	....	....	....	....	....	0.50	0.52
SO_3	....	....	....	....	....	0.10	0.04
Cl	....	....	....	....	....	0.44	0.06
Total	8.0	11.0	2.8	74.1	95.9	100.67	100.40

The composition of the Cardabia sample could be less definitely established, as it was made up of three clays, the composition of each of which is variable within limits.

Table 4 compares the chemical analysis of the sample with that of a hypothetical sample composed of the three types of clays in the proportions shown. The balance of the water found chemically, after satisfying the kaolinite and the mica, was all assigned to the nontronite. The 9A line could be due to talc, pyrophyllite, or a zeolite.

The iron and alumina of nontronites and beidellites are mutually interchangeable within wide limits, accounting for the discrepancy in these figures.

TABLE 4.

Cardabia Bentonite.

—	15 per cent. Free Silica.	20 per cent. Mica (Muscovite or Illite).	25 per cent. Kaolinite.	40 per cent. Nontronite.	Total.	Chemical Analysis.
SiO_2	15.0	10.3	11.6	16.5	53.4	53.51
Al_2O_3	....	5.2	9.9	0.7	15.8	17.65
Fe_2O_3	....	0.8	....	9.5	10.3	8.38
MgO	....	0.6	....	1.4	2.0	2.22
K_2O	....	1.4	....	....	1.4	1.29
Na_2O	....	....	....	....	....	1.53
H_2O+	....	1.4	3.5	8.0	12.9	5.87
H_2O-						7.06
FeO	....	....	....	....	....	0.08
CaO	....	....	....	....	....	0.18
TiO_2	....	....	....	....	....	0.67
CO_2	....	....	....	....	....	0.26
C (Humus)	....	....	....	....	....	0.48
SO_3	....	....	....	....	....	0.58
Cl	....	....	....	....	....	0.41
Total	15.0	19.7	25.0	36.1	95.8	100.17

ACKNOWLEDGMENTS.

The experimental work was carried out jointly by Mr. I. B. Everingham and the author. Circumstances prevent his appearing as joint author. The work was undertaken after consultation with Mr. H. P. Rowledge, Director of the Government Chemical Laboratories, and Mr. C. R. LeMesurier, Deputy Government Mineralogist. I am indebted to them for their interest in the work and for the benefit of their experience. My thanks are also due to Mr. D. Burns for the chemical analyses. Finally, I would like to express my indebtedness to Mr. J. Shearer, Reader in Experimental Physics in the University of Western Australia, under whose direction the work was carried out.

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5.—DIOPSIDIZATION AND HORNBLENDIZATION—IMPORTANT METASOMATIC PHENOMENA IN THE BASIC SCHISTS NEAR SOUTHERN CROSS, WESTERN AUSTRALIA

By

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ABSTRACT.

Amphibole-plagioclase schists are strongly marked by irregular transgressive diopsidic veins due to calcium metasomatism. Some of the veins (which are normally about $1\frac{1}{2}$ inches wide) are almost pure diopside, but others may contain zones of one or more of the minerals grossularite, epidote, calcite and quartz set within an outer zone of diopside.

Metasomatic hornblendites are associated with many veins of diopside as narrow selvages to the diopside veins. The hornblendic rock has developed as a form of " basic front " in that ferromagnesian elements, expelled during calcium metasomatism, have been fixed in the surrounding rocks.

In areas where original bedding planes of sediments or original lava flows are almost obliterated by metamorphism, zones of considerable linear extent, in which diopsidization is prominent, could be readily mistaken for interbedded calcium-rich sediments. The cause of restriction of diopsidization to narrow bands within certain zones is not yet fully understood. The calcium-rich emanations necessary for the diopsidization and related phenomena are thought to have been expelled during widespread alkali metasomatism of basic lavas and sediments.

INTRODUCTION.

While carrying out petrological investigations on about 10,000 feet of diamond drill cores from Nevoria Gold Mine, the writer has been very impressed by the abundant evidence of the role of metasomatism in both ore bodies and country rocks. The following minerals occur as some of the more important products of metasomatism :—pyrrhotite after magnetite in metajaspilite, grunerite after magnetite in metajaspilite, diopside and hedenbergite after amphibole in both amphibole schist and metajaspilite, hornblende after actinolite and plagioclase in amphibole schist and metajaspilite, and anthophyllite after grunerite in amphibole schist. It is the aim of this paper to give a brief preliminary description of the two related phenomena of " diopsidization " and " hornblendization." A more detailed discussion of these, and related phenomena will be undertaken when a series of chemical analyses has been completed.

Nevoria is located 30 miles S.S.E. of Southern Cross in a belt of Pre-Cambrian metamorphosed basic lavas, ferriferous chemical sediments, tuffs and associated rocks which are surrounded by large tracts of granite and granitized lavas and sediments. Most of the rocks appear to belong to the cordierite-anthophyllite subfacies of the amphibolite metamorphic facies (using the nomenclature of Turner and Verhoogen, 1951).

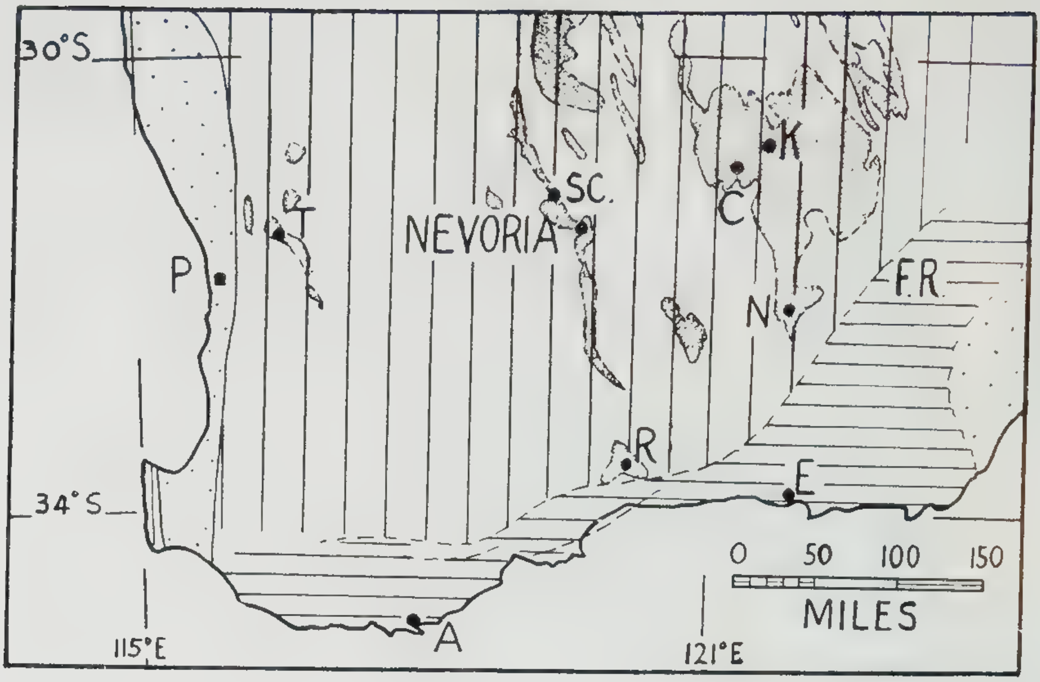

Fig. 1.

Sketch map of south-western Australia to show location of Nevoria. Vertical ruling = Pre-Cambrian granite and gneiss of Central Province; closely stippled belts are mostly Pre-Cambrian basic rocks and sediments of Central Province; horizontal ruling = Pre-Cambrian gneiss and granite of South Coast Province, together with fault blocks of (?) Late Proterozoic sediments; open stippling = mostly Mesozoic and later sediments; P = Perth, T = Toodyay; SC = Southern Cross; K = Kalgoorlie; C = Coolgardie; N = Norseman; FR = Fraser Range; R = Ravensthorpe; E = Esperance; A = Abany.

DESCRIPTION.

Amphibole-plagioclase schists (mostly metamorphosed basic lavas and tuffs) are conspicuously marked in places by diopsidic veins some of which transgress, and others which run parallel to the schistosity. The veins (commonly about $1\frac{1}{2}$ inches wide) are metasomatic, as shown, in many cases, by the attitude of the undisturbed bedding or foliation on both sides of, and sometimes within, irregularly shaped diopsidic veins.

For the purposes of this paper the terms "*diopsidization*" and "*hornblendization*" have been proposed. They are analogous to such terms as albitization and analcitization, and are here used for the phenomena whereby diopside or hornblende (respectively) is produced in a rock by metasomatism.

During the study of the bore cores it has been found practicable to recognize macroscopically four main diopside-hornblende metasomatic assemblages. Each assemblage has been studied in considerable detail in thin section but in this preliminary paper only the most significant features are outlined. The four main assemblages are as follows :

1. Diopside.
2. Diopside enclosing variable amounts of grossularite, epidote, calcite and quartz, the whole enclosed within a prominent but narrow zone of hornblende.
3. Hornblende enclosing diopside, which in turn encloses a zone of calcite.
4. Hornblende enclosing diopside, which in turn encloses a zone of calcite and lenticles of pyrrhotite and chalcopyrite.

In these assemblages diopside contains about 35 mol. per cent. hedenbergite (γ = 1·719, Z $\wedge$ c = 43°) ; grossularite (N = 1·754) contains less than 20 per cent. admixture of other garnet " molecules " ; and hornblende is a common variety (γ = 1·680, Z $\wedge$ c = 20°, X = pale fawn-yellow, Y fawn-green, Z = bluish green).

ASSEMBLAGE 1.

Diopside occurring with accessory zoisite, quartz and calcite is the most abundant assemblage. It occurs in veins in amphibole schists of considerable variety of composition. Veins may run parallel to the schistosity, but more commonly form grotesquely shaped masses which may enclose relict patches of amphibole schist. In this assemblage the grain size of the diopside is commonly 1·5 mm. diameter and individual veins rarely exceed 20 mm. in true thickness. The average grain size of the minerals of the replaced rock is about 0·5 mm. diameter. Hornblende enrichment of the schist at the contacts with the diopside is always present, but rarely sufficient to appear in hand specimen as the bold dark grey selvage so characteristic of more intense calcium metasomatism. (Plate 1, fig. 1).

ASSEMBLAGE 2.

Veins made up mainly of diopside and grossularite are not plentiful, but have been observed in association with all types of amphibole schist at Nevoria. In the typical vein shown in Plate 1, fig. 2, a narrow but prominent hornblende zone encloses a well-marked diopside zone. This, in turn, encloses a zone of grossularite, and this encloses poorly defined zones or lenses of some or all of the minerals, epidote, calcite and quartz. In hand specimen hornblende appears dark greenish grey, diopside is greyish green, grossularite is pinkish fawn, epidote is greasy yellowish green, calcite is white, and quartz is colourless. The grain size of all the minerals usually exceeds 1·5 mm. in cross section, and the veins themselves are commonly 20–30 mm. in true thickness. (Plate 1, fig. 2).

ASSEMBLAGE 3.

Other than the " pure " diopside veins, this is the most common type of metasomatic vein at Nevoria. It is characterized by broad hornblendite zones outside the diopside, and a broad calcite zone as the core. Although the more ferriferous amphibole schists (*e.g.*, anthophyllite—, and grunerite-bearing schists) often carry such veins, they less frequently occur in normal hornblende schists. The grain size of the hornblende, diopside and calcite is commonly 4 mm. in cross section, and contrasts markedly with the small acicular needles of anthophyllite, grunerite and actinolite in the schists. (Plate 1, fig. 3).

ASSEMBLAGE 4.

This assemblage is characterized by the presence of pyrrhotite and chalcopyrite (5–10 per cent.). The sulphides are scattered throughout the central calcitic zone, and are not common in the diopside zone. They are absent from the hornblende zone. A feature of the sulphide-bearing veins is that the hornblende zone (hornblendite) is very prominent, sometimes comprising between one half and one third of the total width of the metasomatic body. The hornblendite has coarse decussate texture with the hornblende crystals averaging about 5 mm. in length. The pyroxenite has coarse granular texture with the average size of cross section of diopside crystals about 6 mm. (Plate 1, fig. 4).

CONCLUSIONS.

The variable thickness of the zone of hornblendite, the absence of grossularite from some veins, and sulphides from others suggest that metasomatizing solutions of variable composition have been active in the area. Some calcium-rich impregnations, for instance, may have been more aluminous than others, and as such allowed the formation of grossularite. A similar result, however, could be obtained if from some rocks alumina was leached more readily than from others. The importance of sulphides in certain veins suggests that some calcium-rich impregnations were not only rich in carbon, but also in sulphur. The variable thickness of the zone of hornblendite may be due to a variable capacity of the country rocks to " fix " those components expelled during calcium metasomatism.

It is significant that in the Nevoria area the diopsidic and hornblendic veins described in this paper have been developed through the activity of calcium-rich impregnations in which carbon dioxide was an important constituent. At the grade of metamorphism (amphibolite facies) at which this metasomatism took place calcite is apparently stable only when the impregnation by calcium has developed in an environment very rich in calcium.

Not only has introduction of calcium caused formation of metasomatic diopside, grossularite, calcite, etc., but it has caused expulsion of iron and magnesium into the surrounding rocks where they have been largely fixed as metasomatic hornblende. The expulsion of this iron and magnesium has caused, in turn, expulsion of small amounts of calcium and alkalies. This is deduced from the presence of calcic rims on the plagioclases in the actinolite schist immediately outside the zone of hornblende enrichment, and bluish tips on the amphiboles in the schists still further away from the centre of metasomatism. There is thus petrographic evidence of the importance in this area of miniature basic fronts and secondary alkali fronts not unlike some of those postulated by Reynolds as resulting from granitization in the Newry Complex, Ireland. (Reynolds, 1944, Fig. 5 on p. 235).

The answer to the problem of the source of the calcium is not easy. It is suggested, however, that the calcium was expelled from basic lavas and sediments during alkali metasomatism which lead to the formation of the abundant granitic rocks nearby. Thin sections of these granitic rocks often show partly corroded plagioclase relicts enclosed in microcline. Thus there is evidence of a vigorous alkali metasomatic corrosion of the plagioclases. Since the calcium, which has obviously been liberated in this process, cannot be accounted for in the minerals of the granitic rocks associated with the microcline paragenesis, it seems that this may be the source of the calcium for the metasomatic phenomena described in this paper.

In areas where original bedding planes of sediments or original basic lava flows are almost obliterated by regional metamorphism (as in the Southern Cross, Ravensthorpe and other goldfields areas in Western Australia) there are zones of considerable linear extent in which diopsidization is prominent. These could be mistaken by the unwary for interbedded calcium-rich sediments. The reason for the pseudo-stratigraphic restriction of diopsidization to certain narrow belts in (apparently) homogeneous rock is not fully known. It is possible, however, that the distribution is related to stresses set up during regional metamorphism and granitization.

The significance of the phenomena here briefly described is that it shows that lenses and veins of pyroxenite and hornblendite may be developed by metasomatism. It is possible that further work may show that some of the lenses of hornblendite and pyroxenite so common in the granitic gneisses and mobilized granites of Western Australia are basified remnants of terrain now engulfed by an advanced front of alkali metasomatism.

ACKNOWLEDGMENTS.

The phenomena described in this paper were discovered while doing petrological work for N.G.M., Limited (in liquidation). Some of the results are hereby published by kind permission of the Company.

The author is indebted to Mr. H. T. Phillipps for his interest and skill in photographing the bore cores.

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PLATE I.

Fig. 1.

Assemblage 1.—Metasomatic diopside in hornblende-plagioclase schist, showing transgression of schistosity in places. Hornblende enrichment at edges of diopside is present but not prominent. Diamond drill core (20 mm. diameter) at 656 feet in Bore 1B. Nevoria Gold Mine. U. of W.A. No. 33873. (Photo., H. T. Phillipps.)

Fig. 2.

Assemblage 2.—Metasomatic vein in hornblende-plagioclase schist comprising zones of diopside (white) and core of grossularite (grey) enclosed in selvage of hornblende (black). Some small calcitic replacements are visible on the right. Diamond drill core (30 mm. diameter) at 751 feet in Bore 10, Nevoria Gold Mine. U. of W.A. No. 33874. (Photo., H. T. Phillipps.)

Fig. 3.

Assemblage 3.—Metasomatic vein in amphibole-plagioclase schist (left) comprising broad zones of hornblende (black) enclosing zones of diopside (grey) and core of calcite (white). Diamond drill core (28 mm. diameter) at 834 feet in Bore 4 Nevoria Gold Mine U. of W.A. No. 33875. (Photo., H. T. Phillipps.)

Fig. 4.

Assemblage 4.—Metasomatic vein in amphibole-plagioclase schist (with apparent dip in core of 30° to right). Vein comprises broad zones of hornblende (black) enclosing narrow zones of diopside (white) and core of mixture of calcite (light grey) and chalcopyrite and pyrrhotite (dark grey flecks). Relation of "basic front" of hornblendite to the calcium metasomatism is apparent. Diamond drill core (20 mm. diameter) at 781 feet in Bore 1B, Nevoria Gold Mine. U. of W.A. No. 33876. (Photo. H. T. Phillipps.)

PLATE I.

Fig. 1.

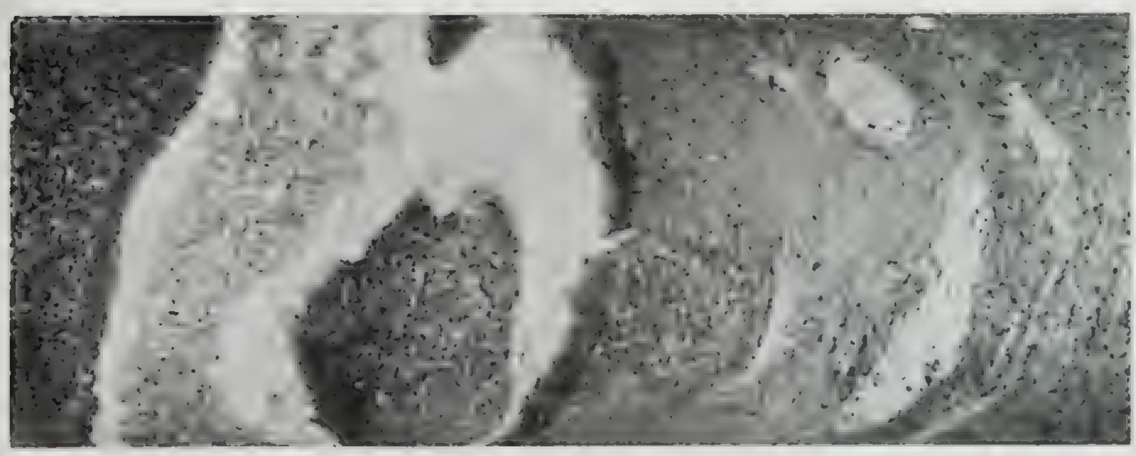

Fig. 2

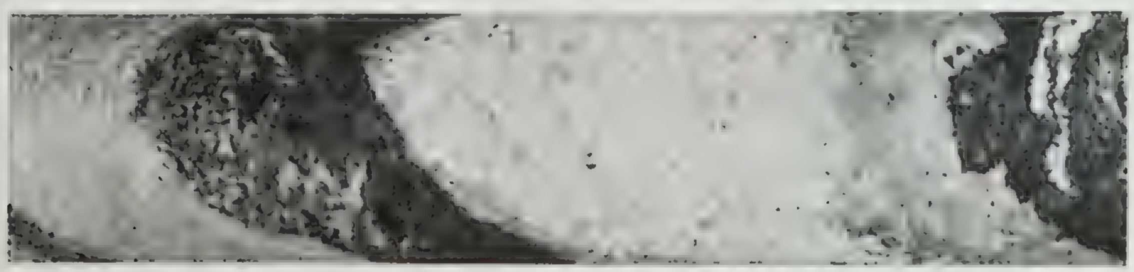

Fig. 3

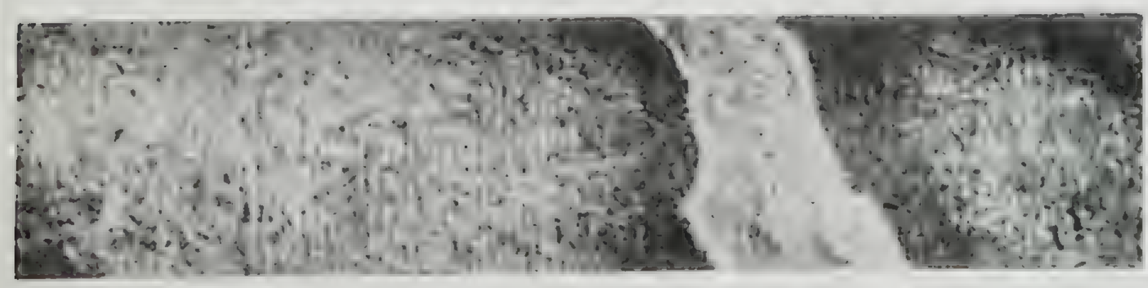

Fig. 4.

6.—FOSSIL SPONGES OF WESTERN AUSTRALIA

By

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Communicated by O. P. Singleton.

Accepted for Publication, 17th April, 1953.

INTRODUCTION.

In 1947, Professor E. de C. Clarke of the University of Western Australia, sent me a collection of fossil Porifera. They are of Miocene antiquity, from the Plantagenet Series (Albany, Cape Riche, and Norseman Beds) which occurs on or near the south coast of Australia only about 200 miles from its extreme west end. We have also for consideration two previous papers concerning fossil sponges from the same series : one by G. J. Hinde (1910) and the other by Chapman and Crespin (1934).

The delay in reporting requires explanation. It happens that a number of leading paleontological societies have begun cooperation leading toward an extensive, several-volume "Treatise on Invertebrate Paleontology." Although the bulk of my research has been on living sponges, its editors asked me to monograph the fossil sponges for this treatise. It seemed advisable to do that first, so that the research pertinent to it could then be applied to study of the Australian specimens.

The fossils which we have for consideration all seem to have been in a substratum of silt. This is slightly ferruginous, but more than ninety percent siliceous. It consists of fine grains, principally less than one micron in diameter, very loosely conjoined if at all. Most of the grains are amorphous, but a notable part of them are whole or broken sponge spicules. It is clear that the stratum was laid down adjacent to a region in which sponges throve. As pointed out in various of my papers, for example, that on Bermuda, sponges today reach maximum abundance in estuaries, just far enough out at sea for complete oceanic salinity to be established. Obviously it is river-borne material that encourages Porifera, the details being still unknown. It is furthermore evident that at the distance from the river where sponges thrive, the coarser debris will have been dropped, but not the finer silt, so that the latter accumulates around the Porifera.

We may therefore conclude that the region under consideration was (when our fossils were living organisms), just off shore from a river—the bigger the river, the farther off shore. All the fossil sponges are lithistids, which would seem to indicate a depth of 20 to 200 meters.

The fossils which we have for consideration are densely packed full of silt just like that of the country rock—pink and crumbling, and full of sponge spicules. This complicates identification. The fossil is a sponge, and full of sponge spicules, but because exactly such spicules permeate the surrounding material, most of those which happen to lie inside the boundaries of the fossil

are certainly foreign to it—perhaps all are—and yet those proper to it may be mingled with the foreign ones. How can one discriminate ? Only the conjoined skeletal elements (the desmas) are certainly proper.

The Lithistida still live, and from study of living forms we conclude that the group is polyphyletic. Nevertheless, it is so distinctive, and convenient in paleontological study, that for the latter it should be treated as an order of the class Demospongea of the phylum Porifera. Today lithistids are rare as compared to other sponges, and probably this has always been more or less true, but because of their coherant framework their likelihood of successful fossilization is disproportionately great. Therefore they are outstandingly important in the paleontology of Porifera.

The Lithistida have long been grouped into sub-orders, according to the type of skeletal element present, these elements being called desmas. From time to time a few fossils have been found whose desmas were difficult to allocate, being somewhat intermediate between the sorts typical of the suborders. Other unusual situations involve fossil sponges having desmas in one place characteristic of one suborder, but elsewhere having desmas characteristic of another suborder. Our Plantagenet fossils possess both of these ambiguities to a distressing extent. We may also recall the abundant presence of obviously foreign sponge elements in them.

Nearly all fossil lithistids have conspicuous cloacas, although sponges in other orders often lack such cavities. Much of the classification of lithistids has therefore been based on the size and shape of the cloaca. Our Plantagenet fossils are notably lacking in cloacal cavities ; this is yet another item which adds perplexity.

In other respects, the fossils under consideration are suitable for study. They have been very little weathered, or crushed, or metamorphosed. They have been skillfully removed from their placements, well-packed and otherwise cared for.

We may first describe a collection of fossils from a place 20 miles south of Ravensthorpe, to the west of the Eyre Range. This would be near the coast, and west of Hopetoun.

The types are preserved at Geology Dept. University of Western Australia.

DESCRIPTION OF SPECIES.

Phylum PORIFERA

Class DEMOSPONGEA

Order LITHISTIDA

Suborder RHIZOCLADINA

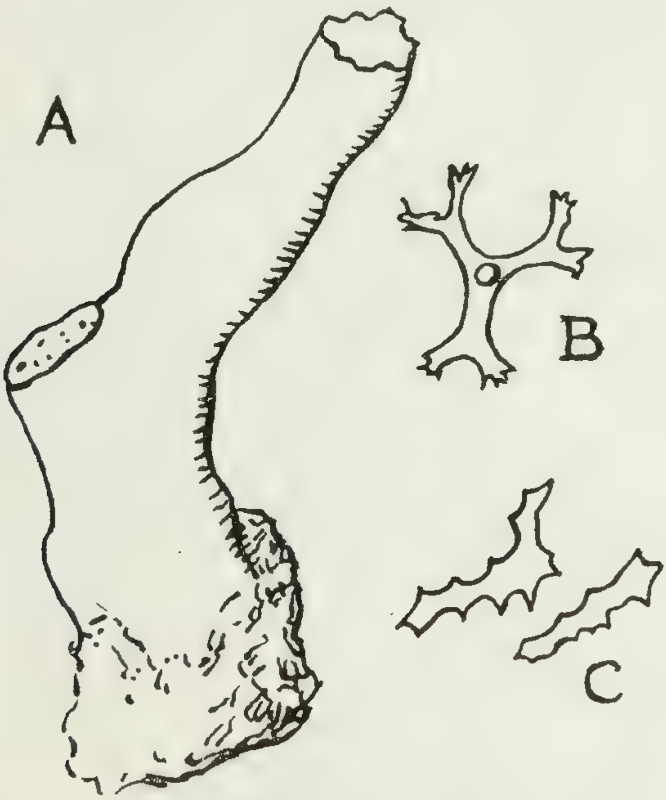
Family **KALIAPSIDAE**

Genus **CORALLISTES** Schmidt 1870, p. 22

Corallistes australis new species.

Specimen number 23735. This is a twice bent lumpy cylinder, which had been branched, and a second fragment, a truncated cone, that probably had been connected. The diameters range from 1·5 to 3 cm. The over all

length of the larger piece is 11 cm. Much of the surface retains the well preserved, dense, lipostomous dermis, even the fine wrinkles in it being still visible. Unfortunately there has been complete or almost complete loss of all evidence as to pores, oscules, and cloaca if (as is probable) there had been a cloaca. In the interior traces of canals can be found, in spite of the dense packing of silt. These that have been observed are about 1 mm. in diameter, and are perpendicular both to the surface and to the longitudinal axis of the sponge. There may have been a long, narrow cloaca following the course of the longitudinal axis.



Text figure 1.

A. Sketch of the sponge, x 5/6.

B. Cladome of a dermal triaene, x 80.

C. Fragments of desma skeleton, x 100.

The skeleton of the endosome is a reticulation of desmas, very firmly cemented together. Only fragments of them could be detached for microscopic study. They are rather more like rhizoclad desmas, but enough like tetraclad desmas to render identification perplexing. The dermis, less than 100 microns thick, is finer grained than the endosome. In many places only the slightly smaller desmas could be located. In a few places it was possible to see the heads or cladomes of triaenes, whose long, straight fourth ray or rhabd penetrated into the interior, perpendicular to the surface. Each of the three clads were dichotomously branched, as is commonplace, but were further again branched at the tips into several crooked fine brachlets.

The cladome shape, and the ramose form of the shape, are distinctive.

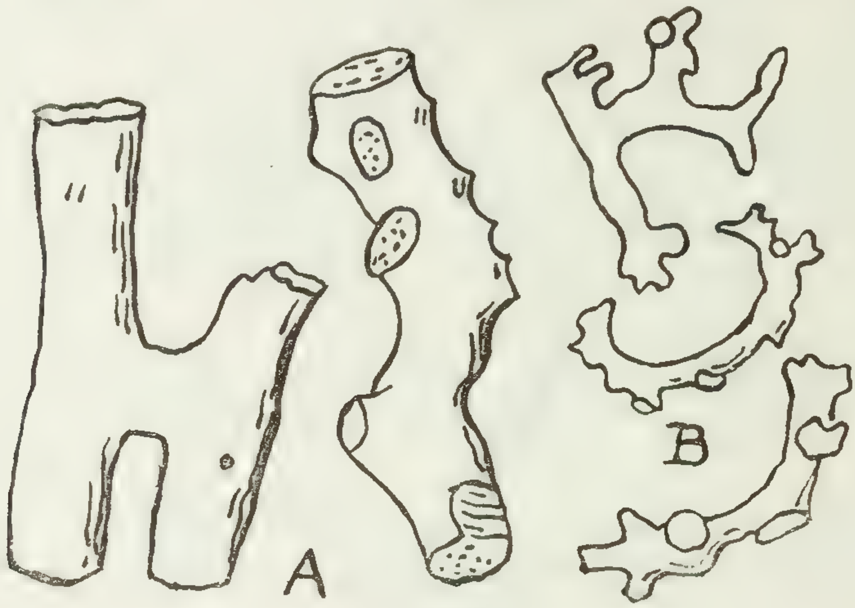
Corallistes is chiefly a recent genus, but is has also been found throughout the Cenozoic, world wide.

Family SCYTALIIDAE

Genus STACHYSPONGIA. Zittel 1878, p. 129

Stachyspongia neoclavellata (Chapman and Crespin).

Specimen number 23732. This comprises two fragments of a ramose sponge. One fragment is simple, the other is " H " shaped. The diameter is about 1 cm. and the length about 6 cm. The nearly straight specimen shows a number of wounds, which may have been places where branches emerged, but is is also beset with large, low conules, nearly 1 cm. in diameter, 3 mm. high. The wounds may merely represent broken-off higher conules. Evidence as to openings such as pores, oscules and cloaca, has been lost.



Text figure 2.

Stachyspongia neoclavellata.

A. Sketches of the specimens, x 5/6.

B. Desmas, x 100.

The certainly proper skeleton consists only of conjoined desmas. These are here regarded as rhizoclad, but attention is called to the fact that they are not typical, but exhibit some of the features of tetraclad desmas.

Chapman and Crespin on pages 115 and 116, describe specimens as *Thamnospongia neoclavellata* and *Thamnospongia subglabra*. The genus *Thamnospongia* Hinde is tetraclad, with especially tuberculate endosomal desmas, and with distinctive phyllotriaenes in the ectosome. Neither of these features is described by the authors. The two species are illustrated by their plate IX, figures 16, 17 and 18. All three of these photographs closely resemble specimens number 23732. The descriptions on pages 115 and 116 will also fit the present specimens. The opinion is therefore here ventured, that we have for consideration a single species, *neoclavellata*. It best fits Zittel's genus *Stachyspongia*, although not typical of that, nor of any other existing generic description.

Stachyspongia has hitherto been recorded only from the upper Cretaceous of Europe.

Genus ZOSTEROSPONGIA new.

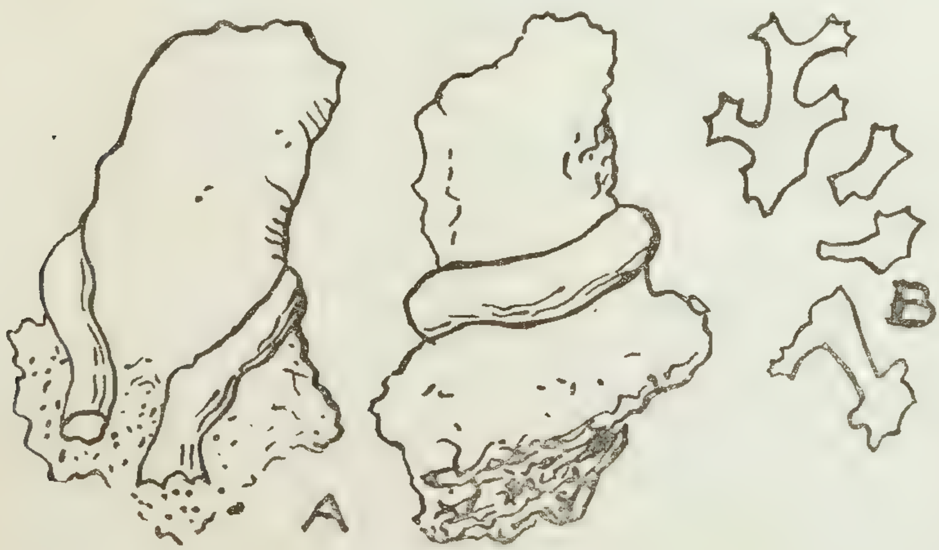
This genus is here established in the family Scytaliidae for an elongate cylindrical lithistid sponge which grew in a most unique manner around another sponge, constricting it. The type and only species is the following :

Zosterospongia thaumasta new species.

Specimen number 23841 B. The constricted sponge (to be discussed further later), is here designated as 23841 A.

The constricting sponge seems to have been circular in cross section. It is 5 to 7 mm. diameter, and 85 mm. long. Its surface is a fine-grained, hard dermis, with no evident openings. It is wrinkled, and the wrinkles are longitudinal. It is probable that there was a terminal oscule and a small longitudinal central cloaca, but the latter squeezed shut by the post mortem shrinkage which produced the longitudinal wrinkles.

It is not possible to be certain what was up with regard to gravity when the sponges were alive, but the relationship to the matrix strongly indicates the placement that is illustrated. Assuming this to be the case, the sponge now being described grew obliquely upward at first, but clung to the other sponge. It then grew horizontally around the other side, still closely appressed to its companion. It finally grew back down, and thus came within 6 mm. of touching its base of origin. It should be kept in mind that lithistid sponges are very rigid. Their course of continued growth may be steered by environmental agencies, but once grown, they are brittle. There is not the slightest trace of any environemental force that could have forced 23841 B to grow in this circuitous fashion. Therefore an innate tendency so to grow is here presumed.



Text figure 3.

Zosterospongia thaumasta.

A. Front and back views of the two sponges, x 5/6.

B. Desma fragments, x 100.

The ectosome is a dense mass of conjoined desmas. The endosome is only slightly less dense. The elements of the skeleton are so firmly united that only fragments can be detached for study. These are rhizoclad, but not typical, as in the preceding genus.

Comment may be made, that in the study of living sponges, we find that when two of the same species adjoin intimately, they regularly anastomose. Obviously the two sponges here described were of different species.

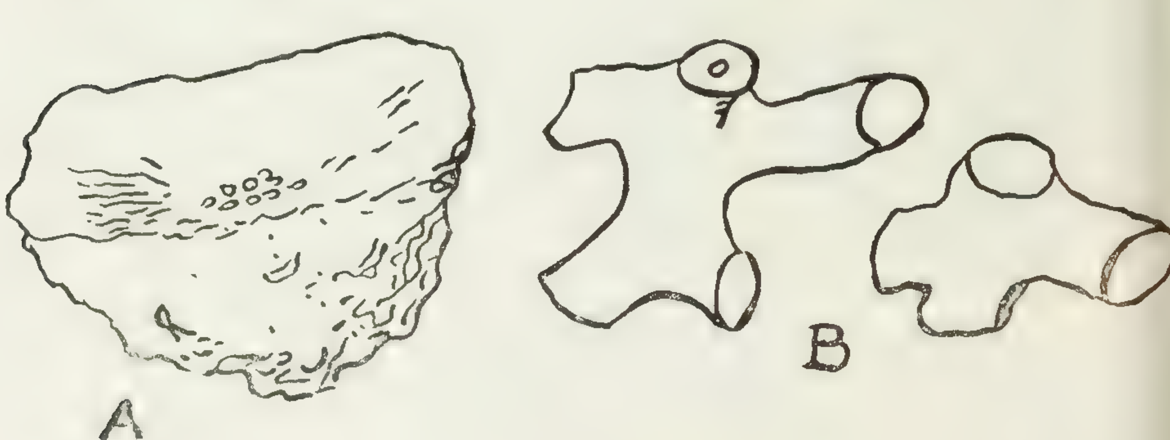
Suborder MEGACLADINA

Family PLEROMIDAE

Genus PLEROMA Sollas. 1888, p. 312.

Pleroma miocenea new species.

Specimen number 23846 A. This is perhaps to be called hemispherical. The upper surface is shallow concave, and fairly regular, but the lower (very convex) surface is extremely lumpy and irregular. The top is 4 by 6 cm. The height is 4 cm. The convex surface is finely porous, probably representing the physiological pores. The exhalent openings on the top are chiefly within a 1 cm. circle in its centre, and each of a dozen or so is nearly 1 mm. diameter. There is some confusion with cavities that may have been carved by environmental agencies during fossilization. No special dermal skeleton is to be found. The skeleton is a rigid conjoined structure of megaclad desmas, their shafts 100 to 150 microns in diameter.



Text figure 4.

Pleroma miocenea.

A. Sketch of the sponge, x 5/6.

B. Fragments of megaclad skeleton, x 70.

This is the first record of *Pleroma* as a fossil. It has been hitherto known for the one species only : *Pleroma turbinatum* Sollas 1888 page 312, recent, from the Fiji Islands, depth 576 metres. This still had loose spicules : oxeas, dichotriaenes, and spirasters, which would usually be lost from fossils. Except for the lack of these uncemented spicules, the miocene Australian fossil agrees closely with the recent *Pleroma*.

Chapman and Crespin, page 115, describe a fossil as *Thecosiphonia lobosa*, new. Their photograph of it (Plate IX., figure 15) reveals a sponge much like 23846 A. They say of it "Dermal layer consisting of small clasping rhabdocrepid desma, as in the living *Pleroma*." This does not describe either *Pleroma* or 23846 A, nor does their description of the endosome. None the less, one must consider a possibility that *miocenea* might fall in synonymy to *lobosa*.

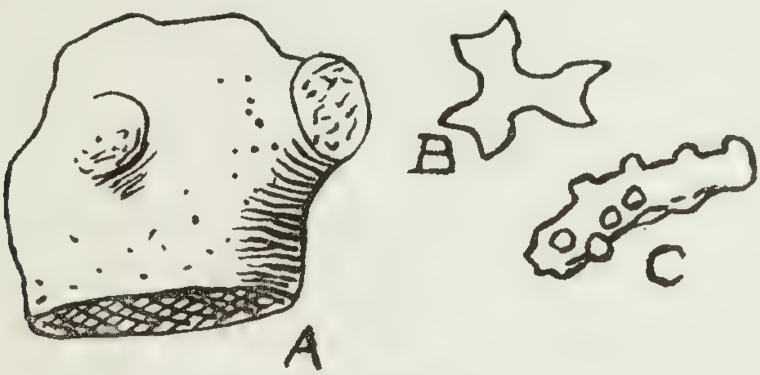
Suborder TETRACLADINA

Family PLINTHOSELLIDAE

Genus PHYMAPLECTIA Hinde 1884, p. 87.

Phymaplectia sterea new species.

Specimen number 23848. This specimen may have been incipiently ramose, but as found is a palmate slab with two or three mammiform projections. One of the projections may be the base of a branch that has been broken off. The dimensions are 2 by 3 by 5 cm., the projections 1 cm. diameter, 1 cm. high. The surface in general is finely porous, probably due to the actual or physiological pores. One or two surface dimples may represent closed oscules.



Text figure 5.

Phymaplectia sterea.

A. Sketch of the specimen, x 5/6.

B. Head or cladome of the dermal triaene, x 100.

C. Fragment of the endosomal skeleton, x 200.

The ectosome comprises a palisade of diochotriaenes, of course with the cladomes at the surface, the long straight rhabds penetrating the endosome. The latter is a stout reticulation of tuberculate desmas.

This species is distinctive for its solidity. Many species of *Phymaplectia* are thinner-walled, even cup or vase shaped.

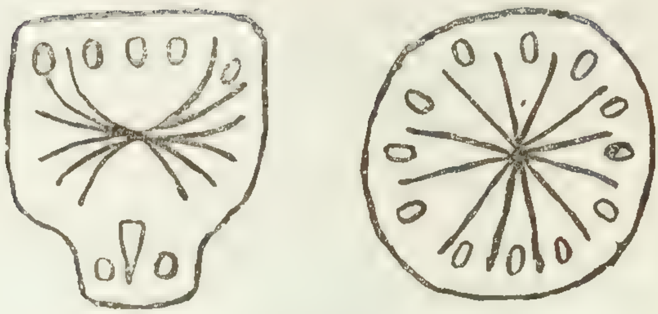
It is here surmised that many other specimens in the present collection, would prove to be congeneric, or even conspecific, with *sterea*, were they better preserved. This is especially suggested for specimens numbers 23849 A, 23840, and 23841 A.

Family DISCODERMIDAE

Genus DACTYLOCALYCITES Carter, 1871, p. 123.

Dactylocalyx callodiscus Carter.

Specimen number 23843. This is a clavate fossil, about 3 cm. in diameter and 8 cm. high. It has a conspicuous dermis, much wrinkled, but pores and oscules cannot be determined. This dermis is all or chiefly a solid mass of desma reticulation. The endosome is somewhat coarser, very brittle.



Text figure 6.

Dactylocalyx callodiscus.
Two of the peculiar perforated silica plates (x 100).

The mass of this sponge contains the usual quota of obviously foreign spicules, chiefly fragmentary, and both in quantity and in variety like the content of the country rock, but with this exception : In this specimen, and only inside it, I find numerous curious perforated plates. These were first named by Carter, 1871, page 123, as *Dactylocalycites callodiscus*, and have aroused much interest.

It has been most commonly assumed, as by Carter, that these are modified discotriaenes, such as characterize the ectosome of the sponges of the family Discodermidae. On the other hand, it has never been proven that they were sponge structures at all. No specimen has yet been found in which they were so placed as to indicate that this was where they originated and belonged. There is a faint possibility that number 23843 is such a specimen, but I am very doubtful about it.

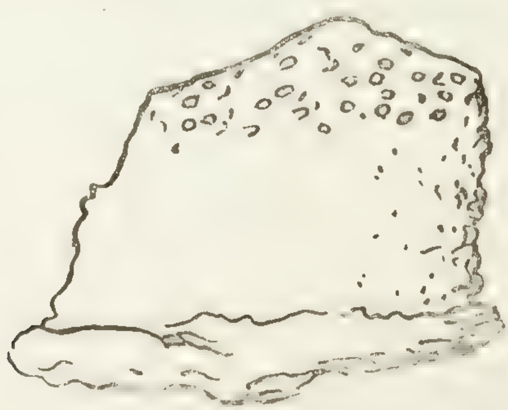
These peculiar fossils are altogether of Cenozoic antiquity, not Recent, and are especially common in Australia and New Zealand.

Family uncertain

Genus TRAGALIMUS Pomel., 1872, p. 202.

Tragalimus amechanus new species.

Specimen number 23840. This is a somewhat acorn-shaped object, 6 by 6 by 6 cm. The most nearly flat side, corresponding to the cup of the acorn, appears to have been covered with a smooth but wrinkled dermis. The rest of the surface is granular, and porous, with pores (or oscules !) about 1 mm. diameter and 2 mm. apart, on centres.



Text figure 7.

Tragalimus amechanus.
Sketch of the specimen, x 2/3.

It is by no means certain that this is all one species ; the top may be one sponge and the bottom another, but the appearance is remarkably like that illustrated by Courtiller, 1861, page 7, for his *Dimorpha balanus*, which is the type of the genus *Tragalimus*.

Neither Pomel nor Courtiller. nor anyone else, has adequately described details of the skeleton of this genus, and therefore its allocation has always been problematical. We are not able to help much now. The whole skeleton is lithistid, but that is the best one can say. Bits taken from various parts of the fossil, and studied microscopically, appear most contradictory. In places the desmas appear to be rhizoclad, but in more places they seem definitely tetraclad. In some places they are lumpy, as in *Phymaplectia*, but mostly they are not. In one place I found numerous phyllotriaenes, but such spicules normally form a dermal or subdermal layer, and nowhere on this fossil could I find them so located.

We may conclude that this is indeed the sort of fossil described by Courtiller and by Pomel, and for a third time confess perplexity as to its skeletal type, and hence, as to its systematic position. Courtiller's records were upper Cretaceous, France. Pomel's may have been Miocene.

Suborder EUTAXICLADINA

Family **ASTYLOSPONGIIDAE**

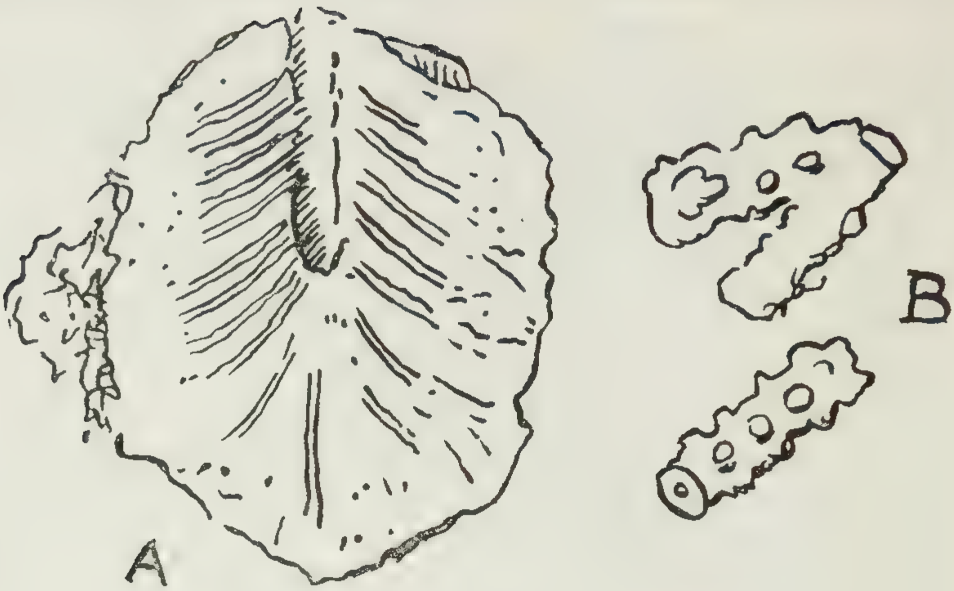
Genus **NEDLANDSIA** new.

This genus is here established in the family Astylospongiidae for a rather poorly preserved fossil which appears to be much like the paleozoic genus *Caryospongia*, but is Tertiary in age. Pending further discovery of related but better preserved specimens from its vicinity, this genus must be regarded as provisional, certainly subject to revision. The type is the one species, *clarkei*.

Nedlandsia clarkei new species.

Specimen number 23846B. This reveals a subglobular sponge which had been 5 to 6 cm. in diameter. It had evidently been exposed and half of it weathered away, revealing a vertical section through its centre. There is visible that which appears to have been a central cloaca, 3 mm. diameter, and 3 cm. deep. What appear to be exhalent canals (apochetes) come to it in great numbers, their diameters about 1 mm., and at 1 cm. from it they are less than 3 mm. apart on centres. They make a radiating pattern. Very few of them flow together.

The skeleton of this sponge either was very flimsy in life, or else has been reduced to this condition during fossilization. In a broken surface, with oblique illumination, it can be ascertained that the pattern as described does have a three dimensional nature. It is most evident on the weathered surface, where the locations of the lithistid skeleton have been slightly less easily eroded than the silt-packed canals. What fragments of skeleton could be found are very tuberculate. This is true of some tetraclad lithistids, significantly including the genus *Phymaplectia*, which occurs near where specimen number 23846B was found. It is also true of the dicranoclone desmas of the suborder Eutaxicladina. I was not able to ascertain whether or not the spicules of 23486B were dicranoclones.



Text figure 8.

Nedlandsia clarkei.
A. Sketch of the specimen, x 5/6.
B. Fragments of the desmas, x 120.

Fossil sponges are often found of Paleozoic antiquity, which as specimens resemble number 23846B in pattern, and in ambiguity. Such are commonest in the Silurian, but are found also in the Ordovician. The similar but often rather well-preserved genus *Microspongia* (incorrectly called *Hindia*) is abundant beginning in the Ordovician and continuing through the Permian. The related *Neohindia* of the upper Cretaceous of Germany is the only Mesozoic specimen hitherto assigned to this group.

The species name is given in recognition of the distinguished paleontologist E. de C. Clarke.

* * * * * *

Professor Clarke also collected a remarkable specimen from the Plantagenet series, at a locality four miles north-north-east of the Kalgan River, on the road from Albany to Gnowangerup. It is composed of silt particles which are almost entirely siliceous, plus very abundant sponge spicules and especially spicule fragments, but these are arranged in a curiously symmetrical pattern.

At the centre is a plug, about 2 cm. in diameter, of blue-green material, probably coloured by ferrous iron whereas the ochraceous larger portion is tinted by ferric iron. There may have been considerable organic matter in the plug, reducing the iron as it decayed. This plug is now chiefly sponge spicular debris, but of such diversity that many species are certainly represented. This plug may have been a sponge with incoherent skeleton, but if so, it cannot now be determined which of the spicules were proper to it. Some recent Porifera secrete no spicules of their own, but pick up foreign spicules of many varieties, depending upon what other sponges occur in the vicinity. The plug may have been such a sponge.

Except on its exposed circular surface, this plug is encased in a wall about 1 mm. thick, very hard, made of spicule fragments inorganically cemented together. There are recent sponges whose proper spicules anastomose, but none in which foreign spicules are conjoined by inorganic means. Those that depend upon foreign spicules lack ability to deposit silica. Around this wall, the silt has been deposited in concentric layers, each layer a cone,

until an inverted cone has been built up, at least 8 cm. in diameter at the top, with a present altitude in its truncated condition, of 7 cm. Around this there had been, and unless weathered or broken off there still is another indurated layer, cone shaped, 1 mm. thick, made of inorganically cemented sponge spicule fragments. Around the outside of this once more occur the larger and larger cones of the concentrically deposited silt plus spicules. This is puzzling.

The whole structure looks like drip stone, but the non-crystalline structure even more than the non-calcareous nature precludes this. It looks like a concretion, but again the microscopic structure rules that out. The layers precisely resemble those that would be quite commonplace if horizontal; they look like layers of silt deposited by gravity—but they are conical in form! Were the layers built up from the outside in, or from the inside out? Apparently twice during their formation, the deposition was almost exclusively of spicule fragments, and at this time silica was also depositing out of solution, but not at other times.

* * * * * *

One who has made extensive study of recent sponges, as well as some study of fossils, may be able to add useful data to papers by paleontologists who have not studied recent Porifera so extensively.

We may thus consider the paper by G. J. Hinde, 1910. In this he describes and figures many sponge spicules, proving conclusively that nearly all the modern orders and families of Demospongia were represented in the Tertiary of West Australia. But he also attempts to assign some spicules to genera.

Prior to 1814, practically all animals which were recognised as being sponges were put in the one genus *Spongia*. Thus generic allocation seemed very easy then. As late as 1860 there were only a few score sponge genera, and they almost corresponded to the present concept of families in their all-inclusive nature. Now we have more than 1,400 genera of recent sponges, and more than 1,200 fossil sponge genera.

Thus when Hinde describes a fossil spicule and adds that "similar spicules occur in the recent genus *Craniella*" he is correct, but has not made an identification, because some fifty other genera also contain exactly the same sort of skeletal element. No genera can be regarded as conclusively identified in Hinde's paper, and only a very few are even "probably" identified.

This sort of difficulty evidently bothered to an especially large degree the efforts of Chapman and Crespin in their 1934 discussion of fossil sponges of West Australia. They were obviously also confused by the fact that authors such as Bowerbank (who certainly influenced his countryman Hinde) used a bewildering variety of names for sponge skeletal elements. In addition to the very excusable errors thus introduced in their paper, one may add with regret that they do not figure even so much as sketches of the skeletal structures of their specimens. Thus it is regrettably the case that most of their identifications fall short of being satisfactory.

An analysis of their descriptions may be given, as follows:—

On page 109 *Tethya* is identified from "globostellate" spicules. This was Bowerbank's term for spherasters. These also characterize other genera, especially *Chondrilla*, which is about as abundant as *Tethya*, or more so. *Latrunculia* is identified from "chessman" spicules. These occur in other

genera, such as *Podospongia* and *Sigmosceptrella*. *Halichondria* is identified from acanthoxeas, but these never occur in *Halichondria*. They do occur in about fifty or a hundred other genera in various families and orders.

On page 110 *Petrosia* is identified from "fusiform acerate spicules" which is Bowerbank's term for oxeas. Oxeas do occur in *Petrosia*, along with other sorts, but they also occur in some five hundred genera ; probably sixty per cent. of all living sponge individuals possess oxeas. *Desmacidon* is also identified from oxeas. One might as well "identify" some particular sort of passerine bird as the result of the discovery of "a feather." *Forcepia* is identified on the basis of forceps spicule, but these occur also in half a dozen other genera, such as *Forcepina*. *Strongylophora* is identified from the occurrence of strongyles. These occur in more than one hundred genera. *Craniella* is identified from protriaenes. Such spicules occur in every genus of the order Choristida, about fifty in all. *Stelletta* is identified from orthotriaenes. These are rare in *Stelletta* but occur in many other genera.

This is to say that isolated sponge spicules of the common sorts are utterly worthless for generic identification, or family identification, and only occasionally even for identification as to what order of Porifera they represent.

Page 111, a fossil is identified as of the genus *Ecionema*, excellently. Another is thought to be *Erylus*, but it is much more like *Geodia*. Another is called a *Caminus*, but it cannot possibly be of that genus, which has a cortex of sterrasters, and no "knobby forms." The specimen probably represents a new genus of the lithistid family Kaliapsidae, but it is inadequately known.

Page 112 began with another specimen called *Caminus* which cannot possibly be of that genus. The same remarks apply to it as to the preceding specimen. Next one is called a *Cydonium*, but so little of it is known that it could be any member of the whole order Choristida. Then one is called *Cydonium ramuliferum*. *Cydonium* is a junior synonym of *Geodia*, and *ramuliferum* is certainly not of this genus. The specimen is unidentifiable. *Theonella* is identified on the basis of spicules which are not characteristic of that genus. *Discodermia* is mentioned at the bottom of the page, and further on the following one.

Page 113 treats three species called *Discodermia*. This genus is characterised by a surface armour of discotriaenes, and no indication is offered that the specimens in question had such. In fact, their surfaces are so described as to make it clear that they did not. The descriptions are complicated by the perplexing use of terms, strongyles being spoken of as having clads, which they emphatically do not, hence one is unable to know what is meant by the author's use of terms in general.

Page 114 begins with another so-called *Discodermia*, which is also unrecognisable, but certainly not in the right genus. Then a very interesting fossil is called *Neosiphonia fungiformis*. It should not be identified with the recent genus *Neosiphonia* because it does not have the spicules which characterise that genus. Its desmas are not described. Perhaps they were as obscure as those in the collection made by Professor Clarke ; if so, the specimens in question would be difficult to place as to sub-order. If they were not obscure, and were figured or described, then this sponge might be allocated as it now can not.

Page 115 includes *Neosiphonia glauerti* which not only can not be a *Neosiphonia,* but—to judge from the description—is of the order Choristida rather than Lithistida. A specimen is called *Thecosiphonia lobosa,* but is described as though it belonged in the suborder Megacladina, not in the Tetracladina with *Thecosiphonia.*

Page 116 includes a species put in *Ragadinia,* but this genus has a dermal armour of phyllotriaenes. Two more generic names, *Corallistes* and *Vetulina,* are hazarded on the basis of individual spicules which are so generalised and commonplace that they are not useful.

Page 117 begins with an encrusting sponge called *Platychonia,* but this genus is for sponges that were erect, lamellate and bifacial. Then another is indentified as *Verruculina,* apparently quite correctly. At the bottom of the page, spicules are presumed to have been of *Rossella* and *Dactylocalyx,* but are very different from those found in such genera. In fact, not even the order of Porifera represented by these spicules can be determined.

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7.—ATMOSPHERIC POLLEN IN THE CITY OF PERTH AND ENVIRONS.

By

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ABSTRACT.

In connection with the problem of hay-fever for which pollen may be one potential cause, the day by day incidence of air-borne pollen grains in and around Perth over a period of two years is described. Pines, grasses, Cypress Pines (*Callitris*) and species of *Cupressus*, *Eucalyptus* and *Casuarina* make the main contribution to the pollen count. Evidence is brought forward to show that the nature and position of the surrounding vegetation is an important factor in the seasonal distribution of pollen, while weather conditions have also to be taken into account. The total pollen catch in the Perth metropolitan area is compared with the pollen catches recorded by investigators in other countries.

INTRODUCTION.

It is generally accepted that pollen is a potential cause of hay fever. This investigation was directed toward determining the types and relative seasonal abundance of pollens in selected parts of the metropolitan area in order that specific information could be available to the medical specialists on allergies.

Plants may be divided into two groups according to their method of pollination. Firstly there are the insect-pollinated types. With many species of this group it is not clear how their pollen could become airborne. Nevertheless there is evidence that at times pollen from such entomophilous plants may be present in the air in garden areas. Secondly, there are those flowers which depend upon the wind for pollination. Members of this group are by far the more important as potential producers of hay-fever. The nature of the pollen grain also makes it apparent that temperature, humidity and wind are important factors in the distribution of pollen.

AREA OF SURVEY.

Since the greatest need for atmospheric pollen research is in the urban areas where the majority of hay-fever sufferers reside, and in view of the fact that the absolute pollen frequency of the air may differ widely at a given moment in various parts of the city and fluctuates from hour to hour and day to day, a number of widely spaced stations were set up in the following locations :—

1. Midland.
2. City.
3. Scarborough.
4. Cottesloe.
5. Mt. Hawthorn.
6. Mt. Lawley.
7. South Perth.
8. Tuart Hill.
9. Fremantle.
10. Wembley Park.
11. University of W.A.

The locations of these stations are shown in the accompanying map (text fig. 3).

METHOD OF SAMPLING.

The gravity slide method as described by Wodehouse (1925), and which has been used in most of the recent atmospheric pollen surveys, was employed. Following Lima (1942), the slides were frosted, leaving a clear surface of

3·6 sq. centimetres, and then coated with methyl green glycerin jelly (Wodehouse, 1935). They were exposed in the specially made standardised device described by Durham (1946). This device makes use of two parallel planes of polished stainless steel held in position by three narrow struts.

The purpose of these planes, apart from rain protection afforded by the upper one, is to cause an even horizontal flow of air between them. The devices were supported on stands three feet high and were placed in suitable positions at the stations listed above. The level of three feet for exposure of the slides was chosen for convenience and on the assumption that it was the one which might be expected to be of greatest importance in relation to hay fever. It may be noted incidentally that it is lower than that used by workers in surveys elsewhere. Pollen from garden plants is believed to have influenced the results only slightly as most of such plants are insect pollinated and their pollen is not so commonly wind-borne. Results show a striking preponderance of the types of pollen from plants in which pollen is known to be wind-borne. The evidence also indicates that the pollen must have been conveyed some distance to the slides. Pollen collected at two high-level stations showed approximately the same incidence and types as at the low-level stations. These were :—the City station at 60 feet and the University station at 50 feet.

It is interesting in this connection to note that MacQuiddy (1934–35) demonstrated that pollen of the country surrounding Omaha in the United States of America, was found in large quantities up to and including an elevation of 3,000 feet during the pollination season.

The slides were examined at a standard magnification of 200 diameters (20 X ocular and 3 objective, Leitz), counting being facilitated by using the mechanical stage. Higher magnifications were used for identifications where necessary.

RESULTS.

A total of 1,317 slides were exposed during the period covered in the first fourteen months of the survey. From these slides a total of 16,881 pollen grains were counted. The distribution of these is shown in text fig. 1. The graph is based on the daily average number of pollen grains per slide, and corresponds with " the number of pollen grains per cubic yard of air as determined by the standard technique recommended by the National Pollen Survey Committee of the American Academy of Allergy, 1942."

Text fig. 1, showing pollen numbers reveals three fairly well defined seasonal periods. (1) A very heavy spring period, August to November. It may be noted that fluctuations occur during late August, September and part of October. These are due to weather conditions. (2) A summer period, and (3) a peak in the autumn. There is reason to believe that the December results may not represent a typical picture of the incidence of pollen for that month, since over the Christmas vacation period not all the stations were continuously operated. In the months of April, May, June and July, the pollen count was very variable in amount and spasmodic in occurrence. Relative non-availability of pollen and inclement weather militated against high incidence of atmospheric pollen. Text fig. 4 summarises graphically the monthly average number of pollen grains per day per slide.

Some attempt has been made to correlate the occurrence of atmospheric pollen with weather data. While it may be seen from text fig. 1 that a number of positive correlations can be made it should be borne in mind that there


TEXT FIG. 1
POLLEN SURVEY PERTH METROPOLITAN REGION
DAILY RAIN IN POINTS
DAILY AVERAGE POLLEN PER. SLIDE
DAILY WIND IN TOTAL MILES
July
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST

are limitations of application. In this connection the following points may be noted :—(1) there must be pollen available, *i.e.*, it must be the flowering season of some species, (2) as one effect of rain is to dampen the pollen and so alter its relative availability, allowance must be made for this, (3) from the above it is clear that wind will become a factor in distribution only when factors 1 and 2 are favourable. The rainfall graph records total points per day. If additional details such as humidity and time of day at which precipitation took place could be included it is possible that more striking correlations would be observed. Correlation with wind is less obvious because as explained above wind can only influence pollen distribution when all the other factors are favourable. The figures used for wind were total daily miles as recorded at the Perth Weather Bureau.

The pollen trapping and counting was continued during the second year, on a modified scale, as a check on the results of the first year. It is interesting to observe that the pollen count over this year, while showing the same seasonal periods and pollen types represented, is much lower than for the 1948–49 season.

From information supplied by Dr. Breidahl it appeared that there was a close correlation between the lessened amount of atmospheric pollen and the number of cases of hay-fever over this period.

It has been possible to assign 95 per cent. of the pollen types examined to their correct plant families, and in many cases also the genus and species has been determined. However, in the case of families such as Gramineae and in the genus *Eucalyptus* further subdivision may only be safely made when correlated with times of flowering of the various species. This point will be referred to again later. Most of the unknowns were distributed over a very wide variety of types. None of the unknowns, however, were of sufficiently high incidence to be a potential cause of hay-fever.

The genus *Pinus* was found to be by far the most important (text fig. 2) from the standpoint of numbers at least. Pollen occurred in a very well defined period commencing in late July and extending to the beginning of November. A few isolated grains, however, appeared on the slides at periods throughout the year. These are believed to represent stale pollen grains which had either been released into the air from an earlier lodgment or which had settled slowly after wind currents had carried them to great altitudes.

The explanation of the preponderance of *Pinus* pollen lies in the presence of pine plantations as well as of individual trees in parks and private gardens throughout the metropolitan area. The other conifers, *Cupressus* and *Callitris* are both important and show a well defined season extending over August, September and October.

Grass pollen was present over the whole year with but a few breaks here and there. Text fig. 2 shows that from a slight but consistent record through August it rises to very great proportions, the peak coming in November. After an apparent lull in December (which may be due to insufficient data as indicated above) the grass pollen is again prominent on the slides until March. Considerable difficulty was experienced in classifying pollen of grasses beyond genera. While the counting of the pollen grains on the slides was proceeding, supplementary field observations were made to determine the species of plants flowering in the vicinity of the stations, particularly grasses, and studies were made of their pollen grains. It was then possible to recognise with reasonable certainty pollen belonging to the genera *Hordeum*, *Avena*, *Briza* and *Ehrharta*, but there always remained a considerable proportion that

could not, with certainty, be identified beyond the Family. For this reason they were all recorded as grass pollen. In this connection it is of interest to note that Jones and Newall (1948) after a special study of the size and shape of 27 species of South African grasses also came to the conclusion that it was impossible to identify most of the common grasses by their pollen.

Some *Eucalyptus* species were associated with the grasses as the main source of pollen through the summer period. Difficulty was also experienced in identifying the species of *Eucalyptus* pollens due to :—(1) the very great similarity of pollen of different species, and (2) the spasmodic flowering times of the numerous species represented in the urban area. Consequently no attempt has been made to group *Eucalyptus* pollens into species. The writer is of the opinion that it may only be possible to classify *Eucalyptus* pollens with any degree of certainty by close observations in the field near the stations at flowering times.

Casuarina was found to have a well-defined although short season of air-borne pollen with its peak in the month of August.

Five other pollen types, *Agonis, Chamaelaucium, Acacia, Papaver,* and species of Composites, although less conspicuous on the graph (text fig. 2), at times were present in the atmosphere in apparently sufficient quantity to be potential cause of hay-fever.

All of the other families found represented on the slides, show a much lower incidence and so will not be considered further in this survey. A list of these is provided in Table I.

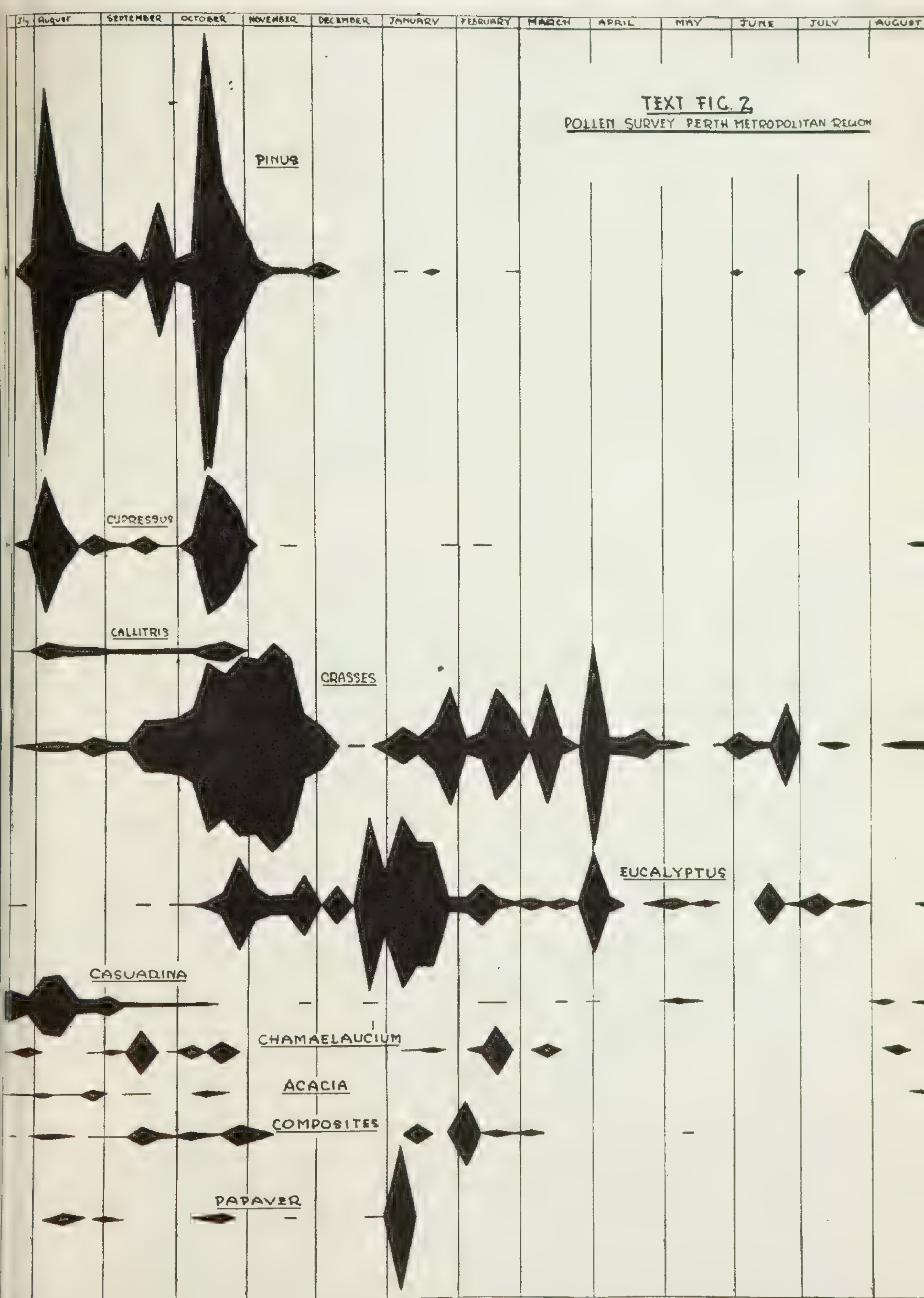
TABLE 1.

List of pollen types in order of aggregate catch expressed in percentages.

Type of Pollen.	Percentages.
Pinus	26·6
Gramineae	23·6
Cupressus	9·2
Eucalyptus	8·85
Casuarina	4·56
Compositae	2·58
Agonis	2·6
Chamaelaucium	2·2
Papaver	1·7
Pelargonium	1·53
Callitris	1·53
Phoenix	0·85
Zea Mays	0·77
Calendula	0·74
Lathyrus odoratus	0·61
Banksia	0·6
Trifolium	0·5
Melia	0·5
Acacia	0·5

The following types rated less than 0·5 per cent

Hardenbergia.
Conostylis.
Stirlingia.
Nasturtium.
Antirrhinum.
Coreopsis.
Anigozanthos.
Triglochin.
Erythrina.



TEXT FIG. 2
POLLEN SURVEY PERTH METROPOLITAN REGION
Jly
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
PINUS
CUPRESSUS
CALLITRIS
GRASSES
EUCALYPTUS
CASUARINA
CHAMAELAUCIUM
ACACIA
COMPOSITES
PAPAVER

Analysis of the results from the individual stations indicated that while marked differences occurred in the incidence of particular pollens from day to day, average values over a period showed no very great differences either in total pollen or in number of species represented on the slides. There were a few exceptions to this where proximity to a possible source led to a local dominance of a particular type of pollen. The marked daily differences occasionally observed between stations could often be correlated with wind direction in relation to possible sources of pollen.

The accompanying map, text fig. 3, also suggests the possible sources of much of the atmospheric pollen of the Perth area. King's Park with its grass and tree species is in a central and elevated position from which pollen could readily become air-borne and distributed over the city. Perth is not yet closely settled and vacant allotments and roadsides support a variety of introduced and native plants. Most of the pollen stations are within easy reach of the influence of open regions still covered largely by native vegetation. However, it is not yet known to what extent native species are implicated as causal agents in relation to hay fever. The report of Zivitz (1942) which indicates that the wind-borne pollen from planted stands of *Casuarina* (Australian Pine) in Florida is capable of producing hay-fever, is, however, significant in this connection.

DISCUSSION.

This survey indicates that there are three fairly well defined seasonal periods in the distribution of atmospheric pollen throughout the year :—

1. A heavy spring period, August to November. The Conifers and *Casuarina* make up the bulk of August-October count, but as the spring advances and then passes into summer the grass pollen becomes increasingly important.
2. A summer period when grass pollen is still prominent but *Eucalyptus* pollen is becoming very important.
3. A less clearly defined peak in the autumn when the two above-mentioned types are the only pollens of importance.

The results of the second year of the survey indicate that these seasonal periods occur from year to year although there may be considerable variation in the quantity of atmospheric pollen.

Similar annual variations were observed by Hyde (1952) in a six-year survey (1943-1948) at Cardiff, Wales. Several factors are no doubt concerned in causing this variation. Two of these may be indicated.

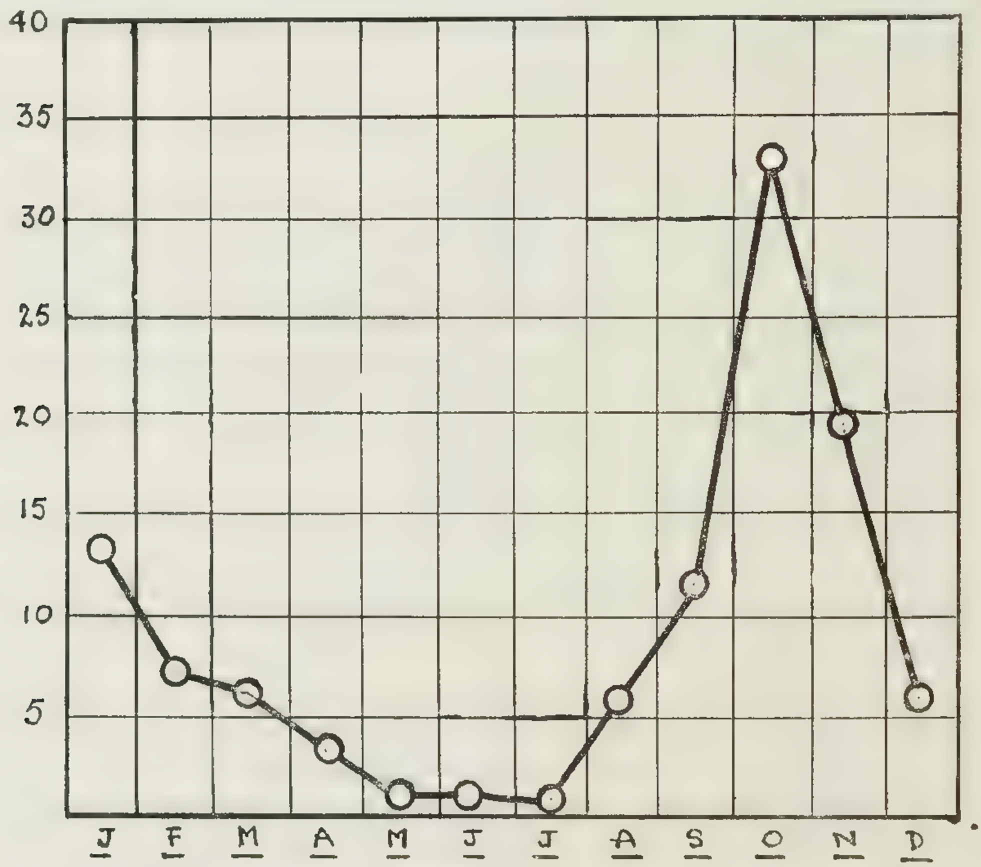
1. Variation in pollen productivity from year to year. This is possibly the most important factor but indirectly may be the result of weather in producing a favourable or unfavourable season.
2. The weather (wind, rain or sunshine) at the time of shedding. Wind direction and velocity exercises a continuous influence on sampling. Rain washes the pollen from the air, but only temporarily.

   Continuous rain would affect the season's catch. Observation indicated that bright sunshine had a relationship to daily pollen liberation. Hyde (1950) recorded the influence of sunshine on the liberation of grass pollens. Percival (1950) working on pollen dispersal in several species found weather to be an important factor. Many flowers were also found to have a marked diurnal rhythm. Working on *Papaver orientale* she found that by 9 a.m. on a sunny morning dehiscence of

the anthers was complete. If weather was sunless total dehiscence was not reached until noon. Continuous rain in the morning prevented both the opening of the flowers and dehiscence of the anthers. However, within 45 minutes of cessation should the sun come out, opening and dehiscence would be complete. Thus morning rain if followed by sunshine need not effect the day's pollen catch. She further observed that if rain began after flowers had opened they did not close until the usual time, leaving the pollen unprotected.

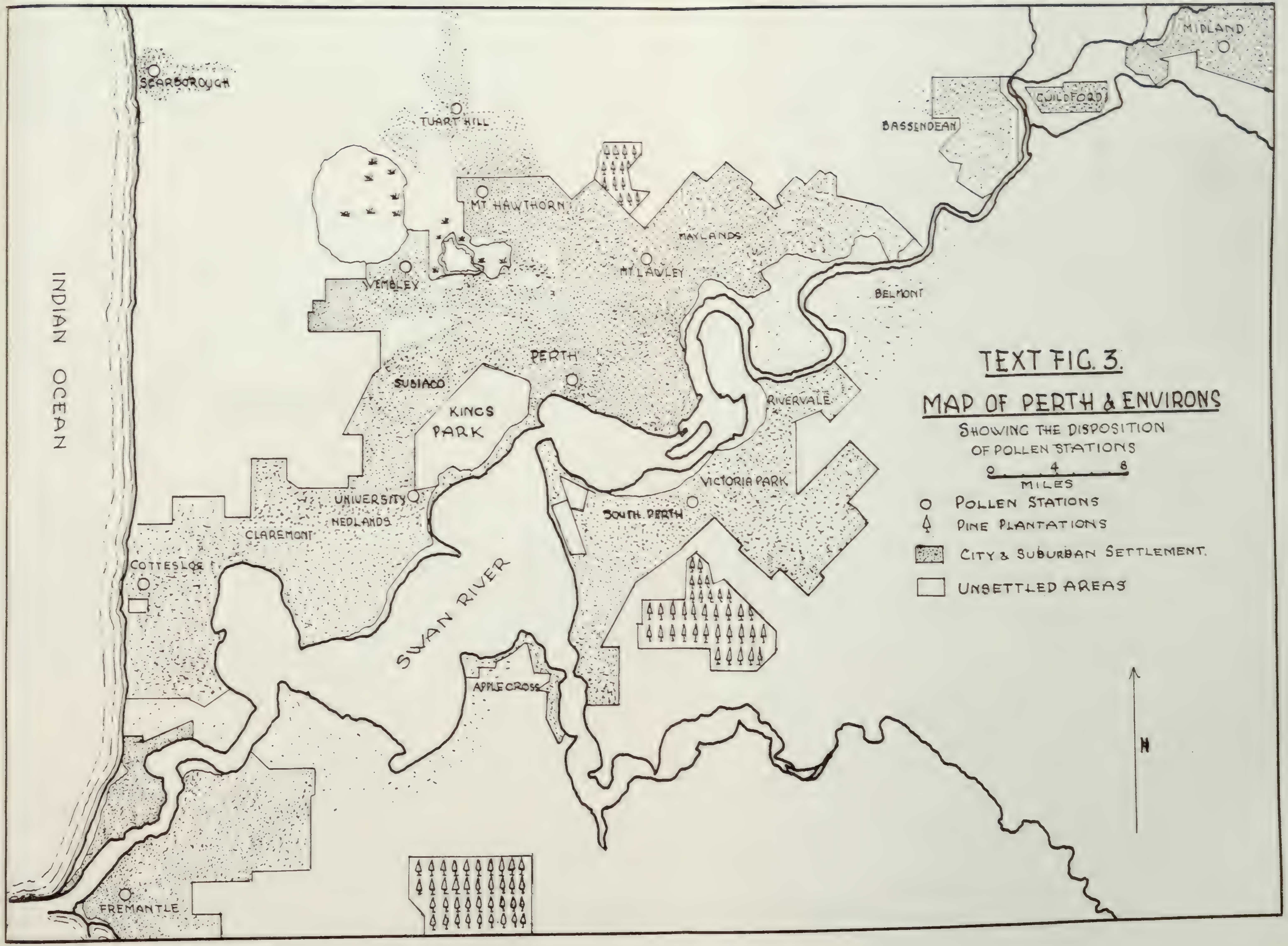
So although text fig. 1 shows evidences of positive correlation between the factors of weather and the amount of atmospheric pollen from day to day, the correlation would be more striking if all the factors of weather throughout the day could have been shown. Nevertheless it is regarded as doubtful if weather has any appreciable influence over the total season's catch.

Although it must be recognised that there will probably be great variation in the production of pollen at different stations throughout any country it is interesting to compare the number of pollen grains per square centimetre per year as recorded by recent investigations.



TEXT FIG. 4.
Graph showing monthly average number of pollen grains per cubic yard of air throughout the year in the Perth metropolitan area.

Firbas and Sagromsky (1946) gives the figures for Germany as ranging from 4,614 to 27,240. Coetzee (1952) in an investigation of the pollen of the grassveld, South Africa, gives 3,051. Figures for the British Isles recorded by Hyde (1952) for eight stations vary from 1,737 to 5,284. The extensive investigations of Durham (1934–35) indicate that there is very great variation in different parts of the United States of America. The count for the West Coast and Texas is mostly under 1,000, which contrasts greatly with records as high as 12,000 to 18,000 for the Mississippi valley and the Eastern parts of



TEXT FIG. 3.

MAP OF PERTH & ENVIRONS

SHOWING THE DISPOSITION OF POLLEN STATIONS

the continent for July, August and September only. Mercer (1939) in Adelaide, South Australia, as the only station for which a full year's results are available, however, records the exceptionally low figure of 825. Incidentally it is also of interest that a comparison of the generalised pollen cycle as found in this survey shows a number of points of correlation with Mercer's results for Adelaide. The following groups show almost identical seasonal distribution in the two States : Grasses, *Pinus, Eucalyptus, Cupressus, Casuarina* and Composites. The present investigation reveals that the figure for the Perth metropolitan area, 1,298, is much lower than those given above, with the exception of South Australia, and the west coast and Texas in U.S.A.

SUMMARY.

This survey shows that the main plant types producing air-borne pollen in sufficient quantities to constitute possible cause of hayfever are :—*Pinus*, grasses, species of *Cupressus, Callitris, Eucalyptus* and *Casuarina*. A less important group of genera, but which nevertheless produce approximately one per cent. or more of the total air-borne pollen, are :—*Agonis, Chamaelaucium, Papaver, Pelargonium, Callitris, Phoenix, Zea Mays* and certain genera in the family Compositae.

Fifteen other pollen types were recorded but it is doubtful if these are ever present in the atmosphere in sufficient quantities to be a potential cause of hay-fever.

ACKNOWLEDGMENTS.

The author is indebted to Dr. B. J. Grieve, Reader-in-Charge for making available the facilities of the Botany Department, and for suggestions in the course of the work. The investigation was commenced on the representations of Dr. Breidahl whom I wish to thank for his helpful interest throughout the survey. I wish also to acknowledge the able assistance given in the pollen counting by Miss E. Summerhayes, B. Roark, and A. Holland. The survey was made possible by a grant from the National Medical Research Council and this assistance is gratefully acknowledged.

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PLATE 1.

Photomicrographs, in optical section, of the main pollen types represented in this investigation. All types are magnified to the same degree.

1. *Papaver* pollen, 24μ.
2. Grass Pollen, 38μ.
3. *Acacia* Pollen, 48μ.
4. *Pinus* Pollen, 41μ.
5. *Callitris* Pollen, 31μ.
6. *Eucalypt* Pollen, 23μ.
7. *Casuarina* Pollen, 25μ.

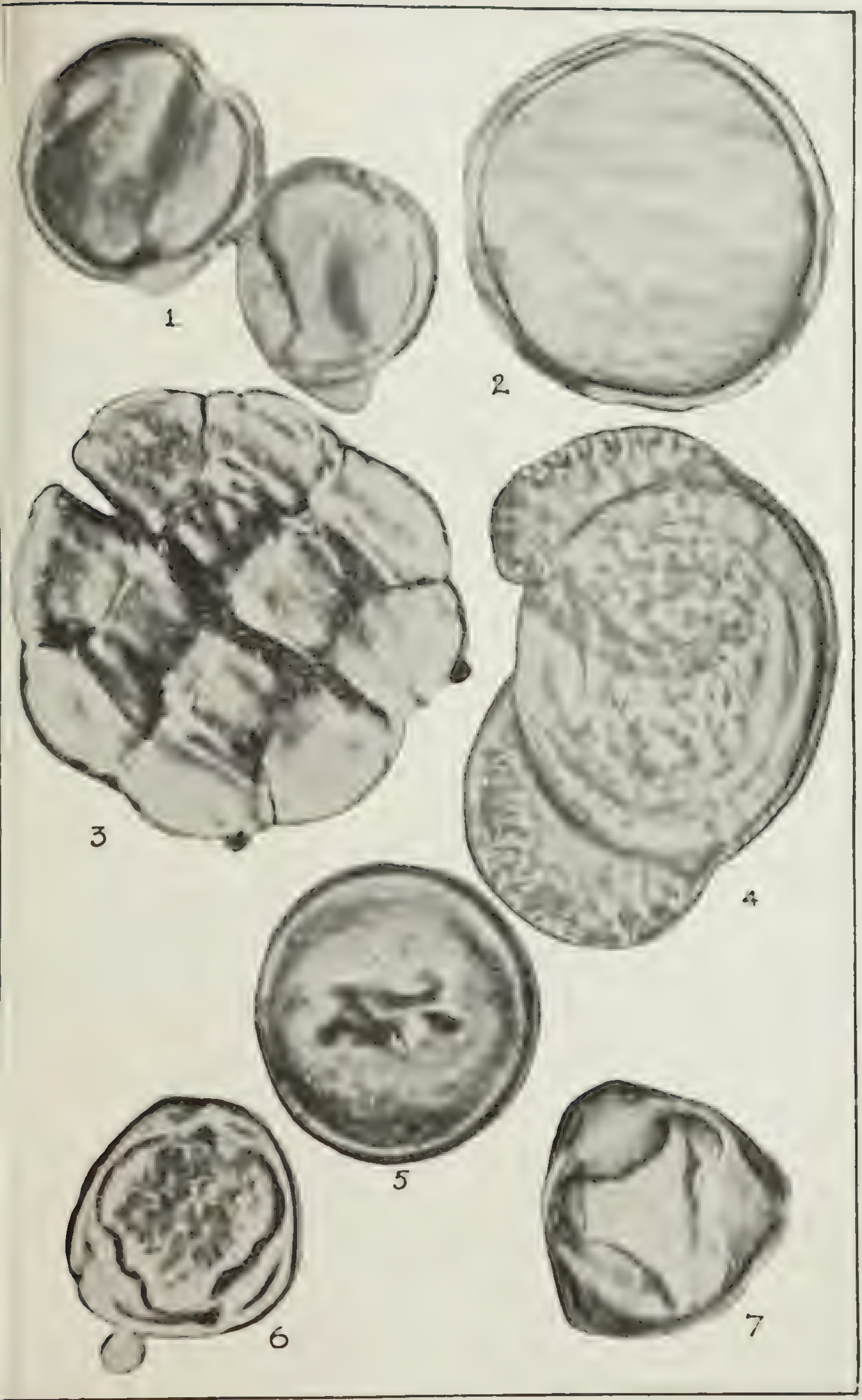

PLATE 1.

GENERAL INDEX.

Generic and specific names in heavy type are new to science.

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